ELECTRICAL CONDUCTIVITY METHODS FOR DETECTING AND DELINEATING SALINE SEEPS AND MEASURING SALINITY IN NORTHERN GREAT PLAINS SOILS

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ABSTRACT

Practical methods, based on measurements of soil electrical conductivity, are given for detecting encroaching saline seeps before damage occurs, for measuring field salinity, for delineating saline seeps, and for identifying recharge areas. Equipment and methods are described in detail, and representative calibration curves for determining soil salinity are given for northern Great Plains soils. Principles and diagnostic criteria are presented.

KEYWORDS: Soil salinity, electrical conductivity, saline seeps, electrical resistivity, salinity, measuring salinity, mapping salinity, diagnosing salinity, northern Great Plains soils, glacial till soils, dryland salinity.

ACKNOWLEDGMENT

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By J. D. Rhoades and A. D. Halvorson[1]

INTRODUCTION

By the time a saline seep becomes visible, the land has already been damaged by excessive salt accumulation. The accumulated salt must then be removed before a subsequent crop can be successfully grown. Hence, a practical method is needed to detect encroaching saline seeps before symptoms appear. Appropriate steps can then be taken to prevent damage and need for reclamation. Because soil salinity increases above its normal level before a seep appears or crop growth is seriously affected, potential seeps may be diagnosed early with a technique capable of detecting atypical levels of salinity. Where saline seeps already exist, we need to assess the degree and extent of damage and to locate their recharge areas.

This manual discusses the use of soil electrical conductivity (EC) sensors and methods for measuring field soil salinity, for detecting and delineating saline seeps, and for identifying recharge areas. Equipment and methods are described in detail, and representative calibration curves for determining soil salinity are given for northern Great Plains soils.

DIAGNOSTIC CRITERIA OF SALINE SEEPS, ENCROACHING SALINE SEEPS, AND UNAFFECTED SOILS

In the cultivated dryland soils of the northern Great Plains, the active root zone is leached with the nearly pure water derived from rainfall and snowmelt during the fall, winter, and spring; and, therefore, this zone is typically low in salinity. Leaching causes a net, downward salt flux that results in the soil profile increasing in salinity with depth through most of the root zone. Typical saturation extract electrical conductivities, EC_e,[2] [3] in millimhos per centimeter, are 0.5, 0.7, 1.0, 1.5, and 2.0 for soil-depth intervals, in feet,[4] of 0 to 1, 1 to 2, 2 to 3, 3 to 4, and 4 to 5, respectively. However, in this climate whenever a saline water table comes closer than about 4 ft to the soil

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[2]Soil salinity is generally defined in terms of EC_e. For details on the method of measuring EC_e, see Appendix C.

[3]A "Glossary of Symbols and Abbreviations" is given in Appendix A.

[4]In most cases, units used herein are English; a "Table of Factors" for converting English units to metric units is given in Appendix B.

surface, the typical net seasonal downward salt flux is reversed by excessive upward flow of water from the water table driven by evaporation at the soil surface and transpiration within the root zone. This upward flow of water causes salts to accumulate within the root zone, and a salt concentration peak results at a relatively shallow depth in the soil profile from the two opposing forces of leaching and upward flow (capillary rise). This condition may be used to identify an encroaching saline seep.

In very early stages of development, the additional water available to the vegetation may produce rank growth and lodging (grain stalk lays over); however, if the upward flow of water and salt is not reversed, salts will accumulate near the soil surface and, eventually, will curtail crop growth. Then, salt-tolerant weeds will invade the area and replace the more salt-sensitive cultivated crop. The soil will remain excessively wet because the salts are hygroscopic and because they reduce water use by evapotranspiration. Such a condition may be termed a "saline seep" and can form without a water table actually emerging at the soil surface. Table 1 summarizes the relative soil properties distinctive for unaffected sites, encroaching saline seeps, and developed saline seeps.

Soil EC can be measured to provide the information required to diagnose encroaching saline seeps and to measure soil salinity. The principles and methods of measuring and interpreting soil EC are described in this manual.

Table 1.--*Diagnostic criteria for distinguishing between unaffected soil sites and encroaching- and developed-saline seeps*

Site type	Salt content	Water content	Soil electrical conductivity
Unaffected	Low, increasing with depth	Low, increasing with depth	Low, increasing with depth.
Encroaching saline seep	Low, increasing to a to a peak at a relatively shallow depth, then decreasing with further depth	Moist surface, becoming wet with depth	Intermediate, increasing to a peak at a relatively shallow depth, then decreasing with further depth.
Developed saline seep	High, decreasing with depth	Relatively uniformly wet to the water table	High, decreasing with depth.

PRINCIPLES OF SOIL ELECTRICAL CONDUCTIVITY

Because most soil minerals are insulators, electrical conduction in saline soils is primarily through the pore water, which contains dissolved electrolytes (salts). The contribution of exchangeable cations to electrical conduction is relatively small in saline soils because these cations are less abundant and mobile than the soluble electrolytes. EC in soils is also affected by the number, size, and continuity of soil pores, as well as salt and water contents.

Rhoades et al. (*19*)[5] showed that the dependence of apparent soil electrical conductivity (EC_a) on EC of the soil water (EC_w), on volumetric water content (Θ), on soil pore geometry (T), and on surface conductance (EC_s) is given by

$$EC_a = (EC_w \, \Theta) \, [T] + EC_s \qquad [1]$$

where $[T]$ is an empirically determined "transmission" coefficient dependent on Θ as

$$T = a\Theta + b \qquad [2]$$

with constants a and b determined by linear regression. Both T and EC_s are properties of the soil solid phase, whereas EC_w and Θ are properties of the soil liquid phase. T and EC_s are related to soil type; hence, for a given soil type

$$EC_a = A_1 (EC_w \Theta) + B, \qquad [3]$$

where $A_1 = T$ and $B = EC_s$. If EC_a measurements are made at reference (that is, calibration) water content,

$$EC_a = A_2 \, EC_w + B. \qquad [4]$$

For any given soil, the EC of a saturation extract (EC_e) is uniquely related to EC_w, so that one may also write

$$EC_a = A_3 \, EC_e + B. \qquad [5]$$

The relation expressed in equation [3], which states that soil EC of a given soil type is a function of its salt and water content, can be used to detect encroaching saline-seep conditions. Soil salinity (of which EC_w is a measure) and water content are relatively low in unaffected soils. Since both increase with depth in the soil (see table 1), so must their product. However, EC_a of the surface soil of an encroaching saline seep site will be distinctly greater, since both its salt and water content are higher than that of an unaffected site; it will at first increase with depth, and then decrease with further depth. Thus, measurements of soil EC_a can be used to detect and distinguish the site types described in table 1. Diagnostic values of EC_a for these site types are given later. Halvorson and Rhoades (7) used this method to diagnose encroaching saline seeps.

To distinguish saline and nonsaline soils, soil salinity can also be diagnosed by making EC_a measurements under conditions of calibration soil water content using the relation expressed in equation [5]. This relation says that for given soil types where water content is at a standard level, EC_a is related to soil salinity. For this purpose, Rhoades and Ingvalson (*16*) recommended making soil EC measurements when the soil water content is at field capacity. This water content (field capacity) is sufficiently reproducible to serve as the reference water content required to establish calibrations between EC_a and soil salinity (EC_e). In irrigated lands, the soil water comes to field capacity shortly after an irrigation.

Under dryland conditions, Halvorson and Rhoades (7) recommended measuring EC_a in early spring or preferably in fallowed land to take advantage of relatively uniform soil water conditions when the soil is also near field capacity. Calibrations between EC_e and EC_a have been successfully determined for many soils in this manner and used to diagnose soil salinity (*7, 9, 15, 16, 17, 18 20*, and J. D. Rhoades and others, manuscript in preparation). Such calibrations for representative northern Great Plains soil types are given in the section "Determining Average Bulk Soil Salinity."

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[5]Italic numbers in parentheses refer to Literature Cited, p. 20.

EQUIPMENT FOR MEASURING SOIL ELECTRICAL CONDUCTIVITY

The basic equipment needed to measure soil EC consists of a combination electric current source and resistance meter, four metal electrodes, connecting wires, measuring tapes, and a thermometer. They are illustrated in figure 1, and details are given in Appendix D.

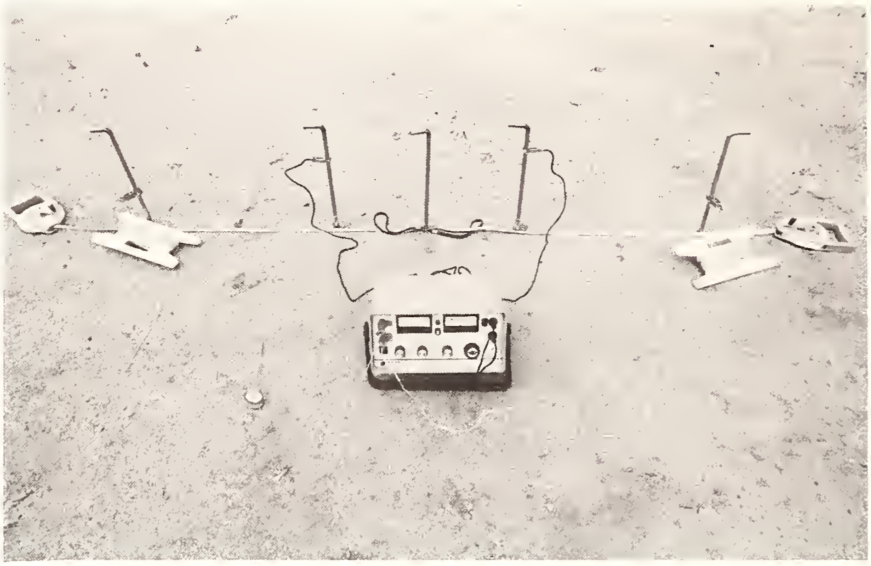

Figure 1.--Four-electrode equipment set up in the Wenner array. The center electrode is used to pin the tapes in the center position and, if desired, to ground the meter (after *15*).

Several suppliers produce combination current source-resistance meters suitable for measuring soil electrical resistance of either handcranked generator or battery-operated types; they range in cost from about $475 to $1,200[6] or more, depending on their accuracy and convenience features. For routine field use, the unit should measure from 0.01 to 100 ohms.

Electrodes may be made of stainless steel, copper, brass, or almost any noncorrosive conductive metal. Electrode size is not critical, except it must be small enough to support its weight and maintain firm contact with the soil when inserted to a 2-inch depth or less. Electrodes 3/8 to 1/2 inch in diameter. by 18 inches long are convenient for most purposes, although for determination of EC_a within shallow depths (less than 1 ft), smaller electrodes are preferred.

Any flexible, well-insulated, multistranded wire is suitable for connecting the electrodes to the meter. A good size for measuring soil EC is 12- to 18-gage wire.

For survey or traverse work, mount the electrodes in a board with a handle so that soil resistance measurements can be made quickly for a given interelectrode spacing. These "fixed-array" units save the time involved in positioning the electrodes. For most purposes, an interelectrode spacing of 1 or 2 ft is adequate as well as convenient (wider spacings require lengthy, cumbersome units).

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[6]All costs reported in this publication were correct as of November 1976.

A simple fixed-array unit is shown in figure 2. If evaluations require EC_a determinations for more than one depth, other sets of electrodes can be added to the board along with a switching assembly to conveniently change connections between meter and electrodes. An example of such a multiple *a* spacing, fixed-array unit is shown in figure 3 and of a switching assembly in figure 4.

For detailed determinations of soil EC by depth or within soil depth intervals, it is convenient to have the four electrodes mounted in a single probe that can be inserted into the soil to different depths. A device developed by Rhoades and van Schilfgaarde (*20*) for this purpose is commercially available. It and associated auxiliary equipment are illustrated in figure 5. More details of the probe are given in Appendix D and figure 24. After the hole is made in the soil with an Oakfield probe, the EC-probe is inserted to the depth(s) of interest and resistance measured.

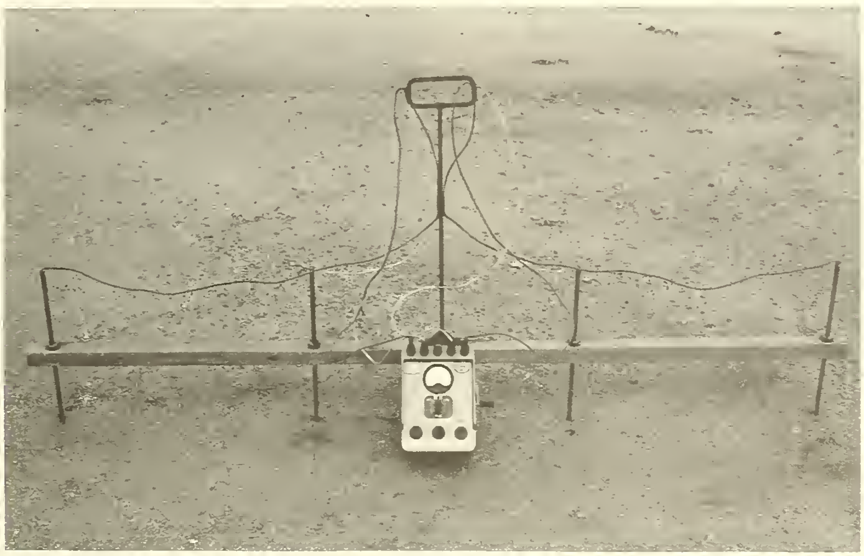

Figure 2.--Fixed-array rig used for making rapid EC_a traverses (after *15*).

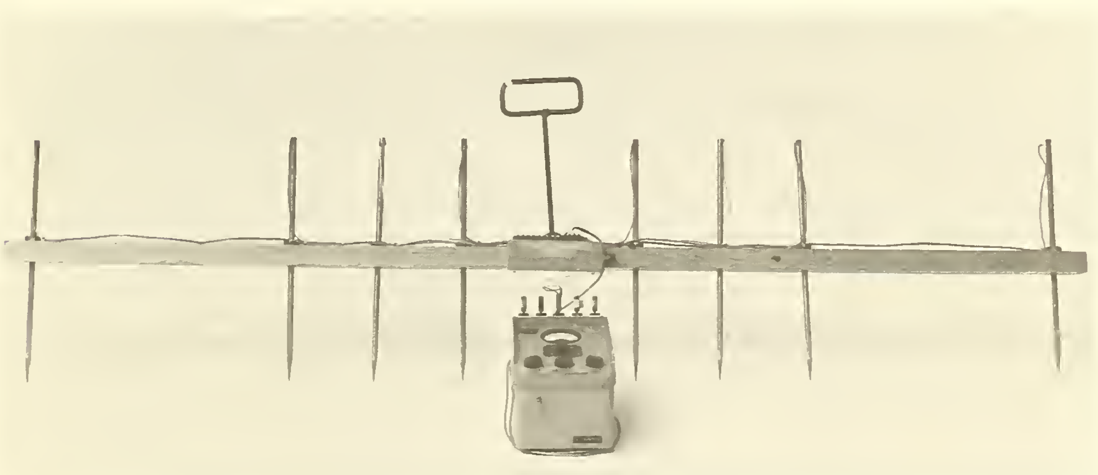

Figure 3.--Multiple *a* spacing, fixed-array unit.

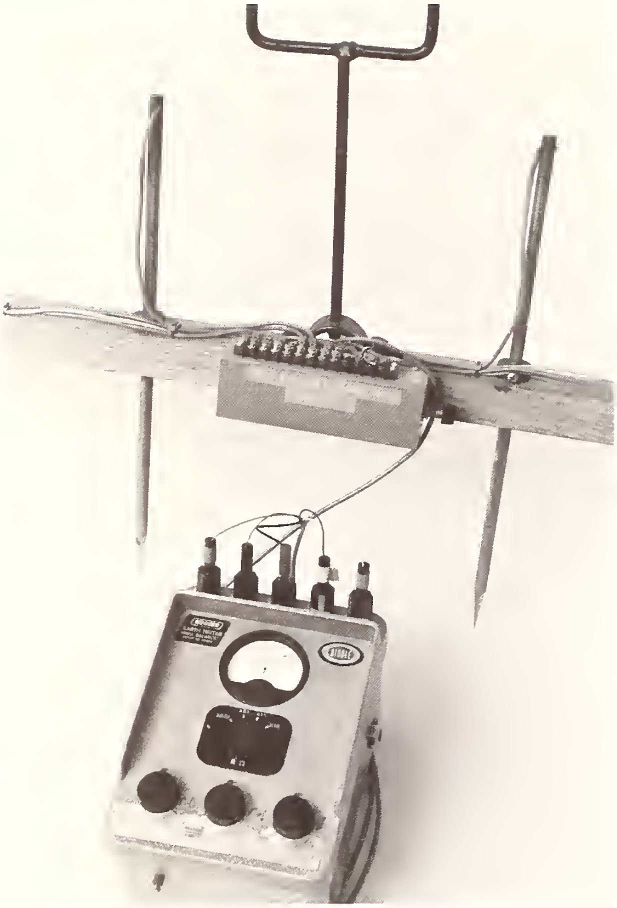

Figure 4.--Switching assembly used with multiple *a* spacing, fixed-array units.

Figure 5.--Soil EC-probe, Oakfield soil sampler, and resistivity meter (after *16*).

METHODS OF MEASURING SOIL ELECTRICAL CONDUCTIVITY

Using Wenner Array

In the conventional method of measuring soil EC (*15*), four electrodes are placed equidistant in a straight line, a configuration called the Wenner array. The electrical resistance across the inner pair of potential electrodes (P_1 P_2) is measured while a constant current is passed between the outer pair of current electrodes (C_1 C_2) (fig. 6). The apparent bulk soil conductivity is calculated as

$$EC_a = \frac{1{,}000}{2\ \pi\ 30.48\ a} \cdot \frac{f_t}{R_t} = \left(\frac{5.222}{a}\right) \cdot \frac{f_t}{R_t}\ , \qquad [6]$$

where R_t is measured resistance (in ohms) for an equidistant interelectrode spacing, a (in feet); at temperature, t, and f_t is a factor to adjust the reading to a reference temperature of 25° C (for this factor see Appendix E);

and EC_a is given in mmho/cm at 25° C. Values of $\left(\frac{5.222}{a}\right)$ for various *a* spacings are given in Appendix F.

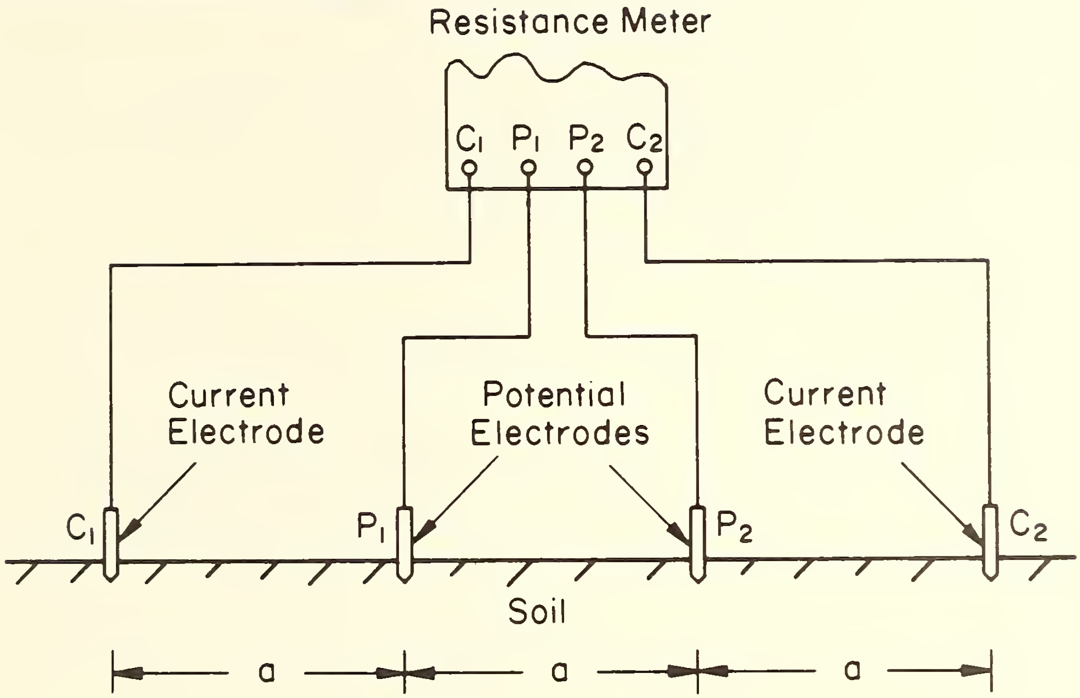

Figure 6.--Wenner array of electrodes used in soil electrical conductivity determinations. *a* represents the interelectrode spacing; C_1 and C_2, the current electrodes; and P_1 and P_2, the potential electrodes (after *16*).

With this Wenner array technique, the EC of a relatively large volume (about πa^3, ref. *15*) of soil is measured, including all the soil between the inner pair of electrodes from the soil surface to a depth about equal to the interelectrode spacing. This volume is illustrated in figure 7. The depth

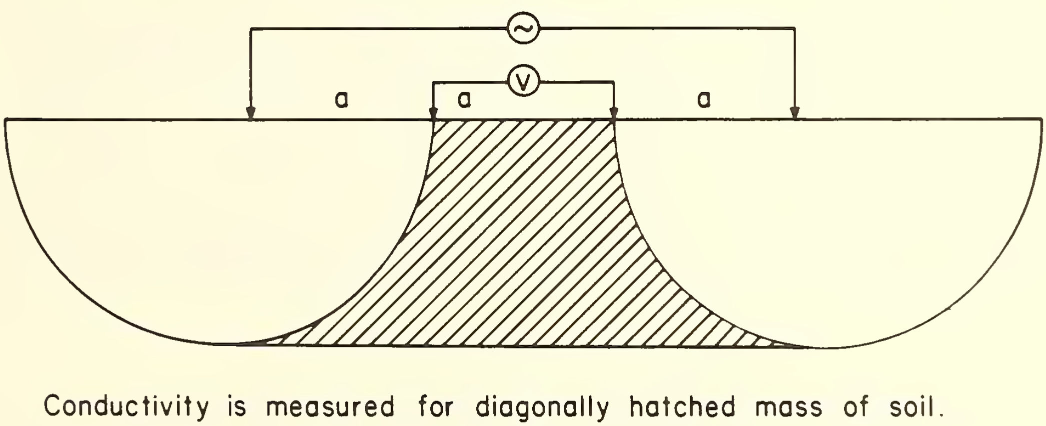

Figure 7.--Volume of soil measured using Wenner array method. Conductivity is measured for diagonally hatched mass of soil.

and volume of measurement increases as the interelectrode spacing is increased, as illustrated in figure 8. Because the current between the electrodes flows in the lateral plane as well as vertical plane, resistances will be influenced by the properties of the earth to the sides and ends of the span of electrodes. Hence, electrodes should not be set up in a configuration where objects, cliffs, or marked changes in soil properties are within a distance of about 2 or 3 *a* to the sides of the potential electrodes and about *a* from the current electrodes. On sloping land, the electrodes should be positioned in a line approximately parallel to the contour of the land.

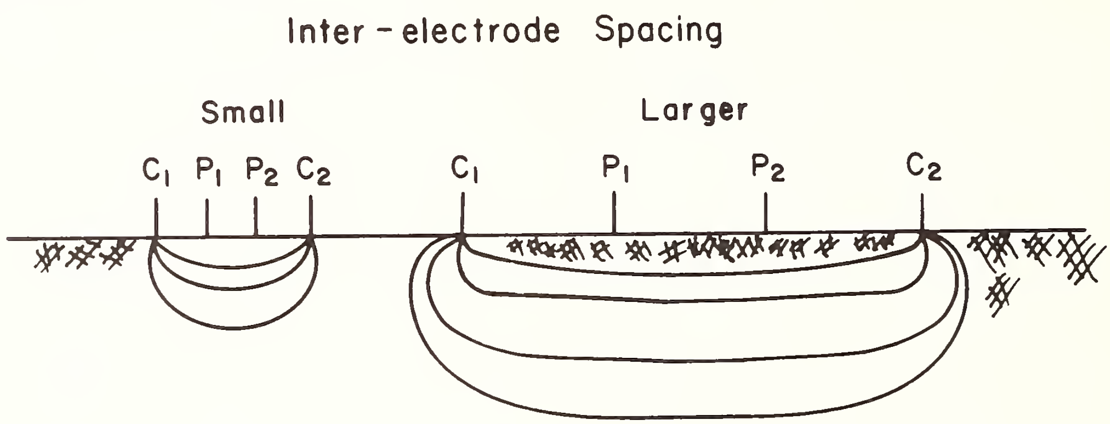

Figure 8.--Schematic showing increased depth and volume of EC_a measurement with increased interelectrode spacing (after *15*). Effective depth of measurement is approximately equal to $C_1 P_1 = a$.

Using EC-Probe

When four-electrode soil conductivity is determined with the EC-probe, the soil resistance is measured with the device inserted into the soil. This probe has dimensions so that when centered at 6-, 18-, 30-, and 42-inch depths in the soil, EC is measured within soil intervals of 0 to 1, 1 to 2, 2 to 3, and 3 to 4 ft, respectively, in a soil volume of about 5.5 in^3 (*20*). Soil EC of such discrete intervals is designated by EC_x, which is calculated as

$$EC_x = \frac{k \ f_t}{R_t} \qquad [7]$$

where k is an empirically determined geometry constant for the probe (19.4) in units of 1,000 cm^{-1}. EC_x is given in millimhos per centimeter at 25° C.

Using Four-Electrode Cell

Soil EC can also be determined using the four-electrode cell and coring technique (*18*). This device and technique are not as convenient for routine field determinations as the preceding methods and hence not generally recommended for this purpose. However, because of the high accuracy of the method, they are useful for calibration and are described in some detail in Appendix G, "Using Four-Electrode Cell."

APPLICATIONS

Determining Average Bulk Soil Salinity

Average soil salinity (EC_e) may be determined from EC_e measurements once calibrations are established between EC_e and EC_a for the soil type(s) in question, provided the EC_a determinations are made at approximately the same water content as that for which the calibrations were made (*7, 15, 16, 20*). A separate calibration for each individual soil of interest is not usually necessary; calibrations are similar enough for soils of similar water holding capacities and textures so suitable salinity appraisals can frequently be made using generalized calibrations (*15, 16, 18, 20* and A. D. Halvorson and others and J. D. Rhoades and others, manuscripts in preparation). If, however, such specific calibrations are required, they are simply established using one of three methods (*15, 16, 18, 20*) described in Appendix G.

Generalized EC_e vs. EC_a calibrations are given in figure 9. These calibrations (A. D. Halvorson and others, manuscript in preparation) were determined in Montana and North Dakota, using calibration methods described in Appendix G, for soils of different types and from different geographical areas having saline-seep problems. The calibrations apply to soils at near field capacity.[7] Because soils of similar textures have similar calibrations (*15, 19, 20*, and A. D. Halvorson and others, and J. D. Rhoades and others, manuscripts in preparation), calibrations are presented by textural groupings. These calibrations may be used for northern Great Plains soils of similar textures to diagnose soil salinity when soil water is near field capacity, such as in the spring of the year or in summer-fallowed fields in dryland areas, or after irrigations in irrigated areas. By far the most dominant soil type in Montana, where saline seep problems exist, is clay loam. The calibration determined for this soil type (A. D. Halvorson and others, manuscript in preparation) is $EC_e = 5.47\ EC_a - 0.47$ ($r = 0.94$).

Some properties of the calibration soils, by textural type, are given in figure 9. If a soil of concern departs markedly in texture and water holding capacity from those of the calibration soils, the calibrations presented should not be used, and an appropriate calibration should be established for the particular soil.

The depth to which average soil EC_a is measured with the Wenner array may be varied by varying the spacing between the electrodes. The effective depth of measurement of soil EC_a (and hence soil salinity) is approximately equal to the interelectrode spacing, provided the soil is essentially uniform in soil physical properties to this depth (*7, 15, 16*). This relation between depth of measurement and interelectrode spacing is illustrated in figure 10, where plots of EC_a (a = 1 ft) vs. average EC_e (0 to 1 ft), EC_a (a = 2 ft) vs. average EC_e (0 to 2 ft), EC_a (a = 3 ft) vs. average EC_e (0 to 3 ft), and EC_a (a = 4 ft) vs. average EC_e (0 to 4 ft) data points all fall near the same line. Thus, by

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[7]In areas affected by saline seeps, soils of higher salinity tend to have higher water contents, because the source of the salts is a shallow water table. Furthermore, soils of seep areas tend to be enriched in clay content. Hence, conditions for a true linear EC_e vs. EC_a calibration are not met (see equation 5). However, for practical purposes, the errors involved are insignificant, and such EC_e vs. EC_a calibrations may be used.

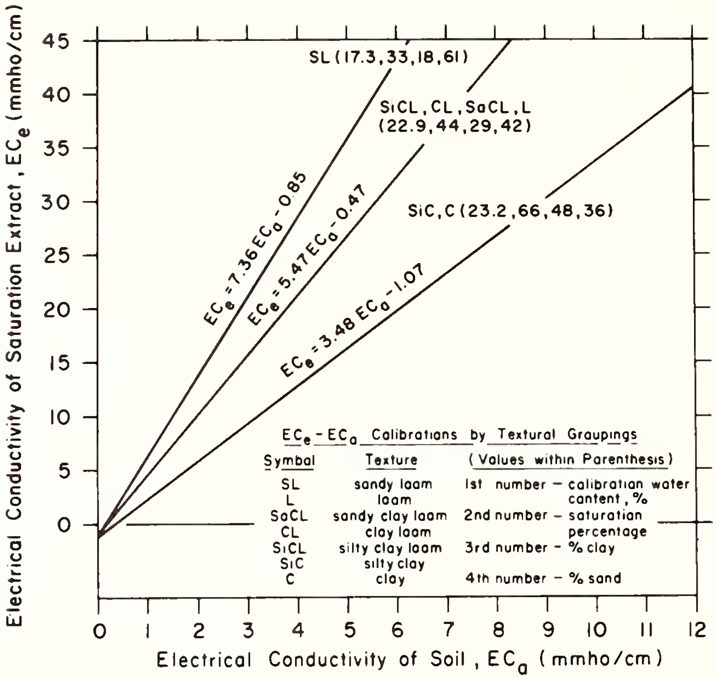

Figure 9.--EC_e vs. EC_a calibrations for representative soil types of the northern Great Plains (after A. D. Halvorson and others, manuscript in preparation).

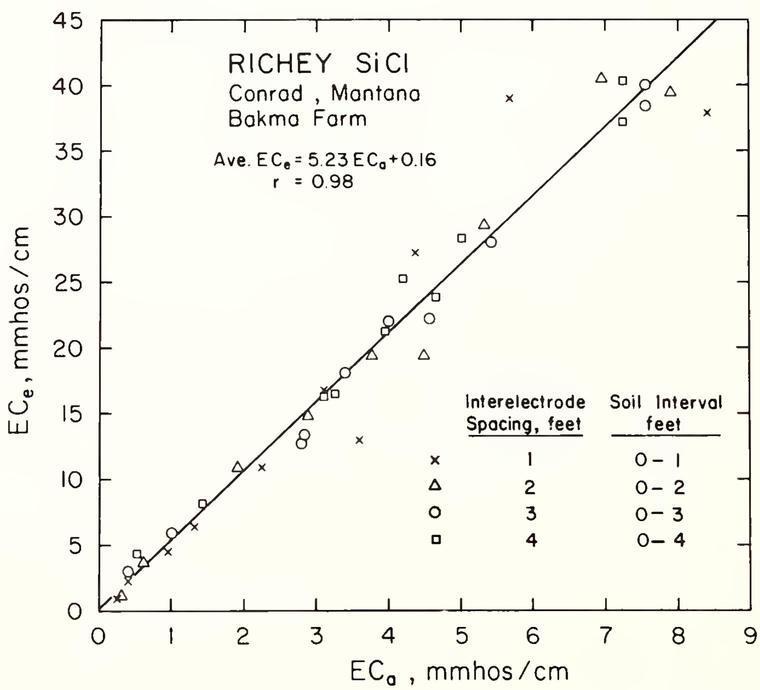

Figure 10.--Relation between soil electrical conductivity, EC_a as determined with interelectrode spacings of 1, 2, 3, and 4 ft measured soil salinity, expressed as EC_e, for average depths of 0 to 1, 0 to 2, 0 to 3, and 0 to 4 ft, respectively, for a glacial till soil near Conrad, Mont. (after *17*).

varying the spacing between electrodes, the average soil salinity can be determined to different depths, provided the soil has a relatively uniform texture through this depth. A single calibration, such as that appropriate to the surface soil, cannot be applied to the subsoil if the latter's texture is appreciably different from the former. For such cases, the methods described in the following section should be used.

Determination of the average bulk soil salinity to a given depth is useful in distinguishing between saline and nonsaline soils. Average bulk soil salinity may also be used, for example, to predict the effect of salinity on crop growth. Salt tolerance data of major crops of concern in the northern Great Plains are given in Appendix H in terms of EC_e to aid in interpretation of findings.

Determining Soil Salinity Within Discrete Soil Depth Intervals

At times, information of salinity distribution with depth or within discrete depth intervals in the soil profile is desirable, such as when sufficient variation of soil texture occurs with depth in the soil profile to preclude the use of the method described in the previous section for accurately assessing soil salinity within a desired depth. For such cases, the EC_a of discrete textural zones within the depth of interest should be determined separately. Then, using the appropriate calibration relation for the textural types encountered (fig. 9), the EC_e for each zone can be established separately and weighted by depths to determine the profile average.

In this section, two methods of determining soil electrical conductivity of a discrete soil depth interval, EC_x, will be presented. EC_x can be calculated from EC_a values obtained at successively increased interelectrode spacings determined using the Wenner array technique and equation [8], after Halvorson and Rhoades (*7*):

$$EC_{a_i - a_{i-1}} = EC_x = [(EC_{a_i} \cdot a_i) - (EC_{a_{i-1}} \cdot a_{i-1})]/(a_i - a_{i-1}) \qquad [8]$$

where a_i represents the interelectrode spacing, and a_{i-1} represents the previous spacing. This equation is based on the assumptions that (1) the depth to which conductivity is measured is equal to the interelectrode spacing, and (2) the stack of soil electrical resistances of a sequence of soil layers is assumed to behave like resistors in parallel (*1*). Example calculations employing equation [8] are given in Appendix I.

Data demonstrating the high correlation between interval soil salinities predicted with equation [8] and those determined from soil analyses are presented in figure 11. Soil salinity by depth intervals within the root zone can be assessed with this method in soils without marked horizontal variations in texture or salinity, with sufficient accuracy for practical salinity appraisal, and without taking soil samples or making laboratory analyses. This assessment cannot be applied to soils with marked horizontal variations of texture or salinity; for such cases, or where more precise determinations are required, the EC-probe method is recommended (*20*). In this method, the EC-probe is inserted into the soil to the desired depth(s), and the EC_x of the soil at that depth (± 3 inches) is determined directly using equation [7].

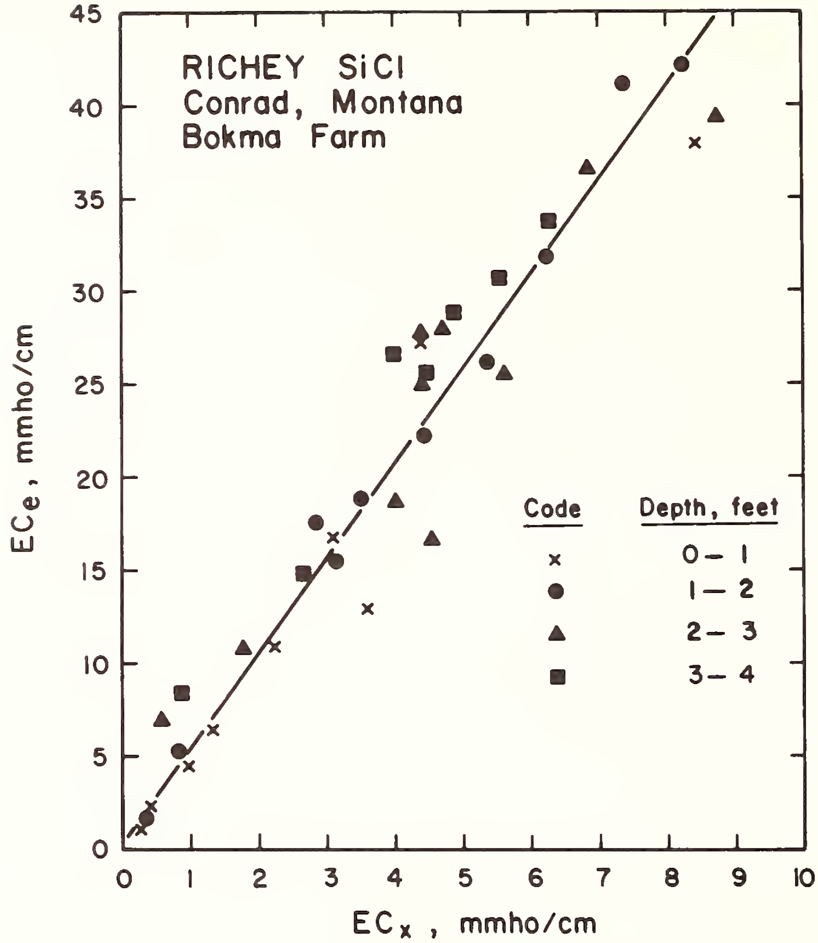

Figure 11.--Relation between EC_x, as calculated with equation [8], and determined EC_e values for soil depth intervals of 0 to 1, 1 to 2, 2 to 3, and 3 to 4 ft for a glacial till soil near Conrad, Mont.

Identifying an Encroaching Saline Seep

Encroaching saline seeps may be diagnosed from either the absolute value of surface soil EC_a or from EC-depth relations.

Figure 12 shows plots of EC_a vs. interelectrode spacing (essentially soil depth) determined using the Wenner array technique for typical Montana glacial till saline seeps, encroaching seeps, and unaffected sites. The EC_a values of unaffected glacial till-clay loam surface soil (0 to 1 ft) are typically < 0.3 mmho/cm, whereas those of encroaching saline seeps are generally ≥ 0.5 mmho/cm wherever water content is near field capacity. The EC_a values of developed saline seeps in such soils usually exceed 1.5 mmho/cm. Analogous values for other soil types are given in table 2. In addition to such characteristic surface soil EC_a values, the EC_a vs. depth curves are distinctive for the different conditions of saline-seep development irrespective of water content (*7*) as described in table 1. EC_a increases with soil depth in unaffected sites, decreases with depth in saline seeps, and increases at first and then decreases with depth in encroaching saline-seep situations. The soil EC-probe (*20*) is ideally suited for determining such EC-depth relations although the calculation method

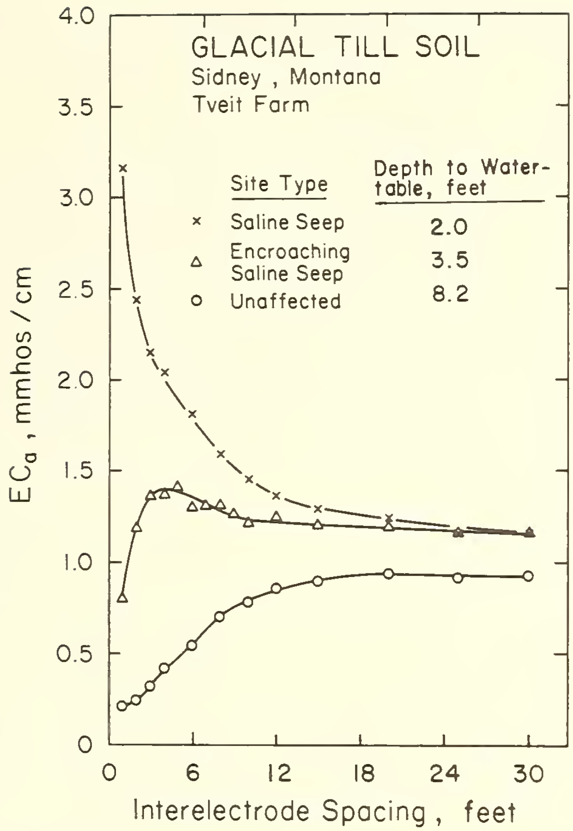

Figure 12.--Relation between soil electrical conductivity, EC_a, and interelectrode spacing for a saline seep, an encroaching saline-seep site, and an unaffected site for glacial till-clay loam soil near Sidney, Mont. (after *17*).

Table 2.--*Diagnostic* EC_a *values for distinguishing among unaffected soil sites, encroaching-saline seeps, and developed-saline seeps for representative soil types of the northern Great Plains*

Soil type[1]	Site condition		
	Unaffected	Encroaching seep	Developed seep
	Millimhos per centimeter		
SiC-C	<0.5	0.8	>2.5
SiCl, CL, SaCL, L	< .3	.5	>1.5
SL	< .2	.4	>1.0

[1]SiC = Silty clay, C = clay, SiCL = silty clay loam, Cl = clay loam, SaCL = sandy clay loam, L = loam, SL = sandy loam.

using expanding Wenner array measurements described in the preceding section (equation [8]), or EC_a vs. a plots, like that illustrated in figure 12, are adequate for this purpose.

Techniques for obtaining EC_a and EC_x vs. depth plots are presented in Appendix I.

Delineating Bodies of Salt-Affected Soil

Once an encroaching saline seep is identified, its extent may be delineated by conventional mapping techniques by using either EC_a or EC_x measurements (*8*). Figures 13, 14, 15, and 16 illustrate the utility of this method. EC_a was mapped of a 100-ft grid over an area of 500 by 800 ft of rolling foothill topography in and about a saline seep in eastern Montana. A map of visual symptoms is shown in figure 13; maps of EC_x are shown in figures 14, 15, and 16 (*8*).

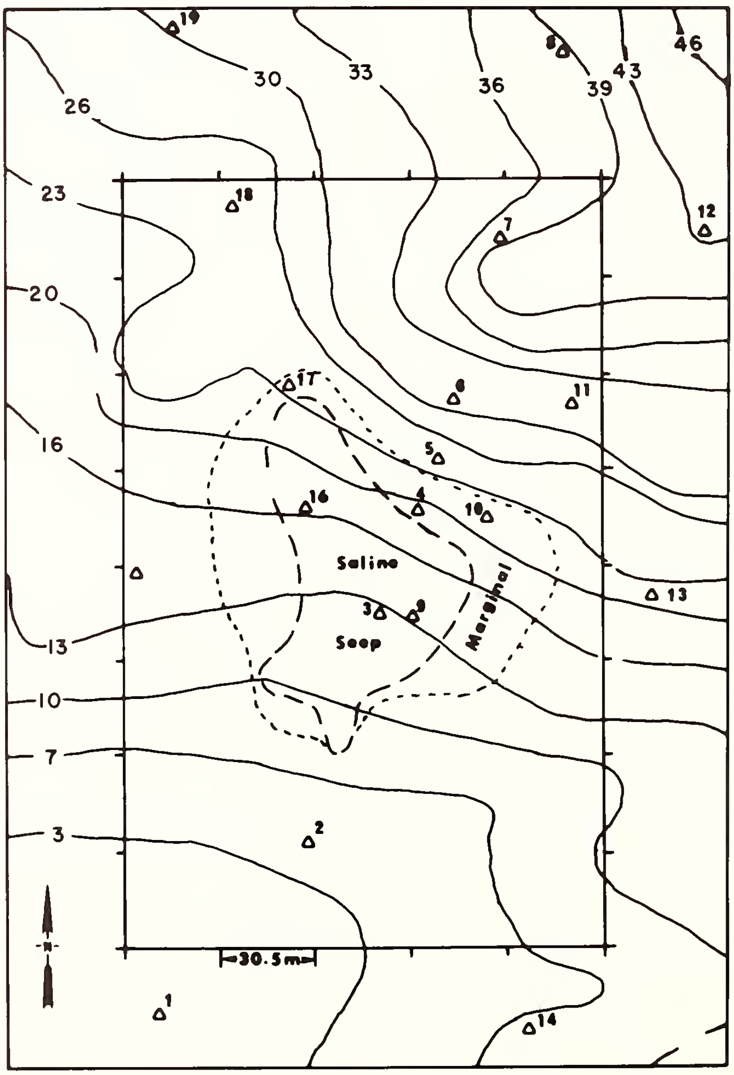

Figure 13.--Surface topography and location of saline seep, marginally salt-affected, and unaffected land (after *8*).

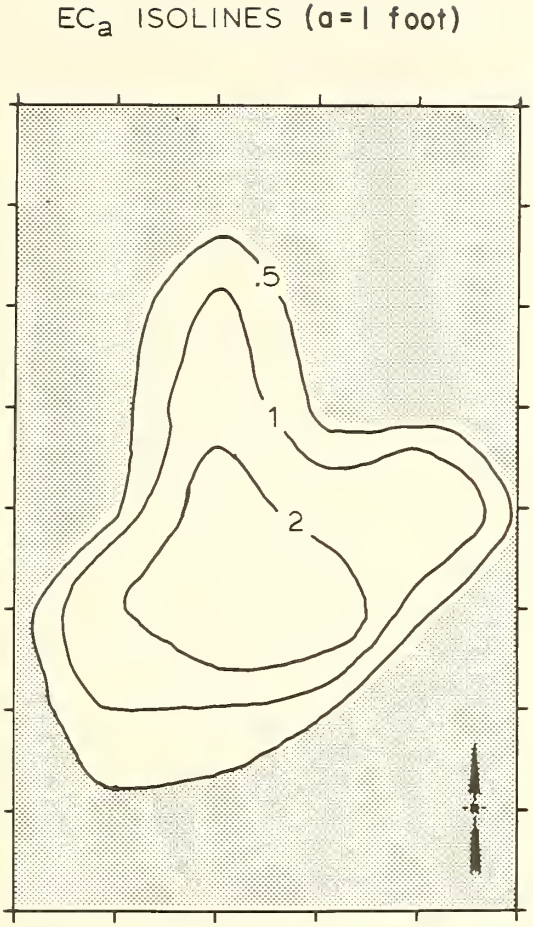

Figure 14.--EC_x isolines for the soil depth interval of 0 to 1 ft (after *8*).

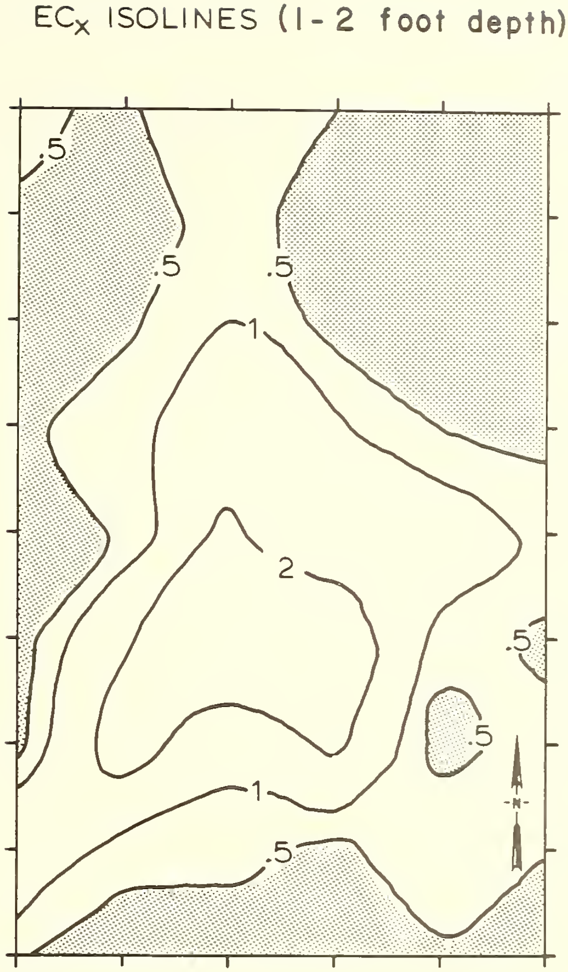

Figure 15.--EC_x isolines for the soil depth interval of 1 to 2 ft (after *8*).

Figure 13 shows the boundaries of the saline seep, the marginally salt-affected area around it, and the corresponding surface topography. The area labeled "saline seep" had almost no plant growth, whereas that labeled "marginal" had visual signs of reduced alfalfa (*Medicago sativa*) growth and poor stand. The remainder of the area had a good alfalfa stand. Figures 14, 15, and 16 show isolines of EC_x for soil depth intervals of 0 to 1, 1 to 2, and 2 to 3 ft, respectively.

From these EC_x maps, the volume of soil (glacial till-clay loam) under the influence of the saline water table can be determined. The soil body mapped with the EC_x isoline > 1.5 mmho/cm was within the saline-seep boundary, whereas the body of soil mapped within the 0.5 to 1.5 mmho/cm EC_x isolines corresponded to marginally salt-affected land. The land mapped with EC_x of < 0.5 mmho/cm corresponded to the area with good alfalfa growth. The subsurface dimensions of the variously salt-affected soil were readily established with the four-electrode soil conductivity mapping technique. While less definitive, maps of EC_a obtained with a succession of increasing *a* spacings can be similarly used for such purposes (*8*).

EC_x ISOLINES (2 - 3 foot depth)

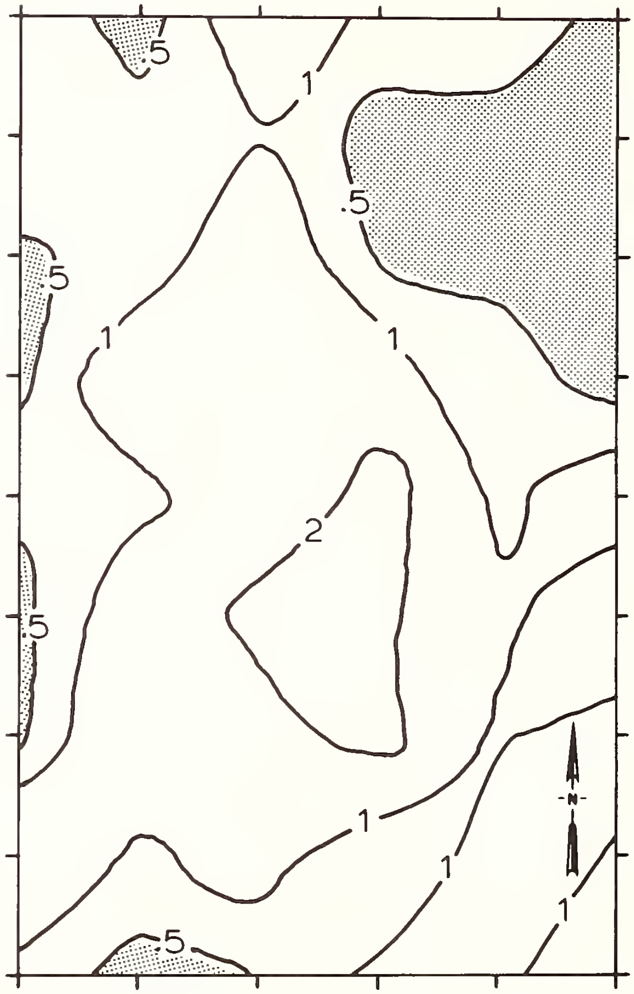

Figure 16.--EC_x isolines for the soil depth interval of 2 to 3 ft (after *8*).

Figure 17 shows the relation between EC_a of the top 1-ft soil depth and depth to water table in glacial till-clay loam soil of Montana (7). Wherever the water table is within about 4 ft of the soil surface of such clay loam, dryland soils, the EC_a of the surface soil increases markedly above its normal "unaffected" value of about 0.3 mmho/cm. Thus, EC_a measurements of just the near surface soil can be used to delineate land under northern Great Plains dryland conditions for which the water table is within 4 ft of the soil surface using standard mapping techniques (*7*, *8*, *17*).

Based on the above observations, we recommend using the EC_a value $\geq$ 0.5 mmho/cm for the surface soil (0 to 1 ft), to delineate glacial till-clay loam soil under the influence of a shallow saline water table, that is, an encroaching saline seep. Analogous values for clay and sandy loam soils are 0.8 and 0.4 mmho/cm, respectively. Alternatively, EC's of deeper soil intervals, EC_x, may be used to delineate the boundaries of encroaching saline seeps.

Techniques for developing soil EC maps are presented in Appendix J.

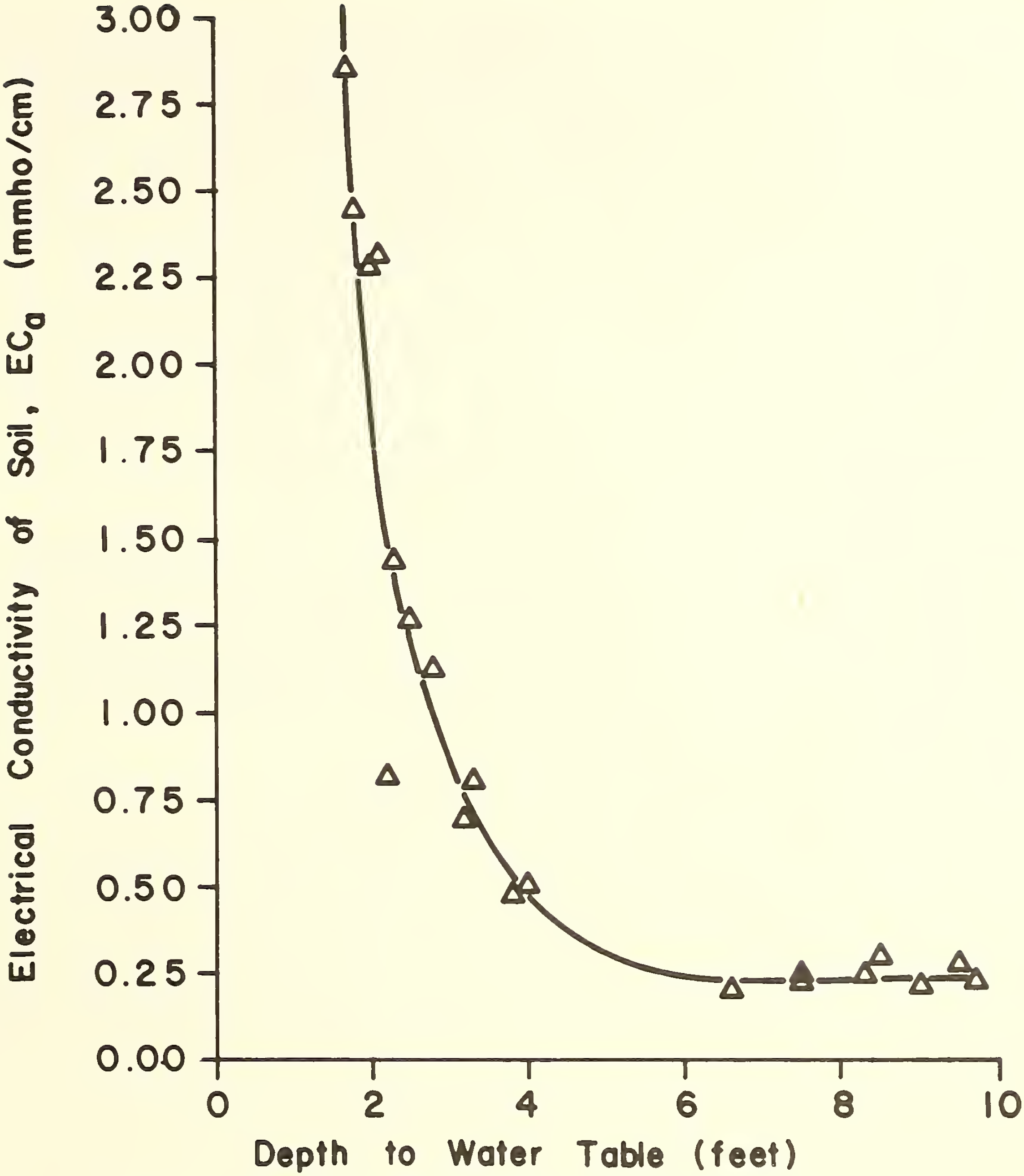

Figure 17.--Relation between EC_a (a = 1 ft) and depth to water table in dryland glacial till soil (after 7).

Estimating Depths to Discontinuities in the Soil Profile or to the Water Table

Depths to bedrock or water table are not required, as demonstrated in Appendixes C and D, to detect the condition of an encroaching saline seep. Measurements of EC_a or EC_x are directly related to exactly those soil properties (salt and water content) that are unique and distinctive of encroaching saline seeps and nonaffected areas. Since this technique is so simple and reliable, methods of detection by such indirect determinations as measuring actual depth to water table and bedrock are not advised. Yet, in some cases,

such information can aid in identifying recharge areas and in choosing the most appropriate crop to plant in the area to intercept some of the excess percolating water. For this reason, a brief discussion of the use of soil EC measurements for estimating depth to water table and bedrock will be given.

Primary use of soil EC determinations, prior to using them for salinity appraisal (*16*), was to estimate depths to subsurface discontinuities. Standard techniques for such estimates are amply described in the geophysical literature (*4, 11, 13, 21*) and need not be repeated here in detail.

Halvorson and Rhoades (*7*) used the *a* values, corresponding to breaks in slopes of EC_a vs. *a* plots, to estimate depths to bedrock and water tables in areas surrounding saline seeps to aid in identifying the recharge area. Such a plot is shown in figure 31 (see p. 42). The profile log at this location showed glacial till to a depth of 6 to 8 ft where another, denser till deposit was encountered which continued to a depth of about 18 ft where shale rock was found. The changes in slope in figure 31 at depths of about 6 and 18 ft correspond to these discontinuities in the profile.

Rhoades (*15*) used plots of accumulative EC_a to estimate depth to water tables in alluvial soils (see fig. 18); detailed calculations for this method are explained in Appendix I. Such a plot is given in figure 33 for the location discussed above. The discontinuity at 8 ft corresponds to the change in till deposit found at that depth. Under conditions of simple geologic stratigraphy, such as that of the example location, reasonable success can be achieved

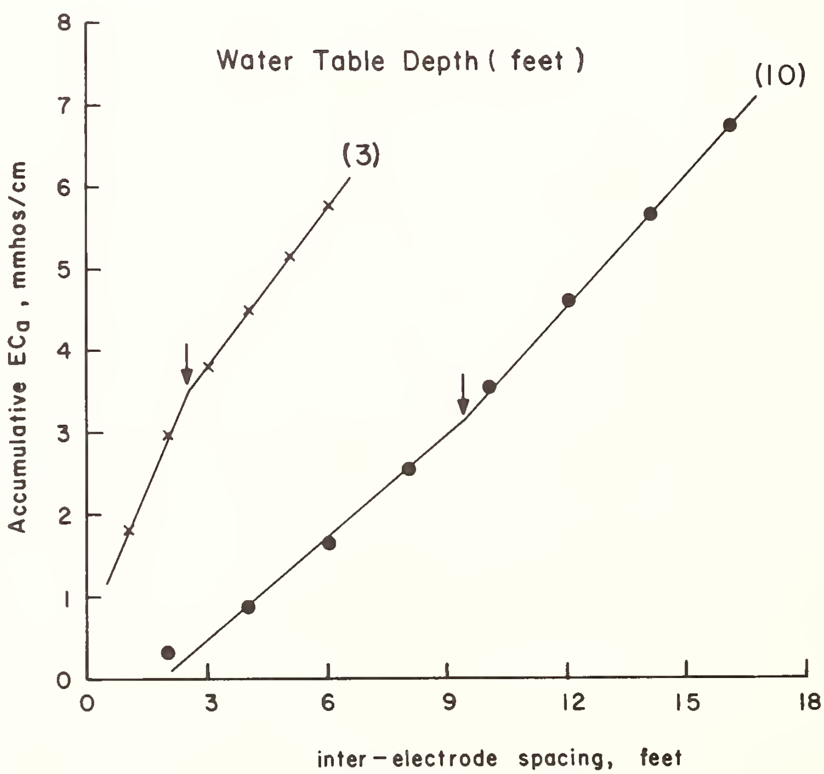

Figure 18.--Relations between accumulative EC_a and interelectrode spacing for conditions of water tables at 3- and 10-ft depths in alluvium (after *15*).

in these determinations. However, such interpretations become complicated in multilayer systems, especially if the layers are thin or if the zone of saturation occurs in a thin aquifer. Therefore, while the methods generally cannot be recommended for this purpose, useful information can often be gained when the user has a thorough knowledge of the existing geologic conditions and experience in making such interpretations, especially if complementary seismic refraction soundings are also made.

Rhoades (*15*) discussed the use of supplemental seismic refraction information to distinguish between breaks in accumulative EC_a vs. a plots (such as in fig. 18) caused by textural or consolidation discontinuities and those associated with a water table. For further details on seismic refraction techniques, see Griffiths and King (*4*), Dobrin (*3*), or other references on methods of seismology (*21, 22, 23, 24, 25, 26*).

Identifying Recharge Areas of Saline Seeps

Although the methods described herein cannot directly identify or delineate the recharge source and area of a saline seep, maps of EC_a or EC_x aid appreciably in this regard (*8*). The subsurface configuration of the salt and water table affected soil becomes discernable in EC maps such as those shown in figures 15 and 16. For example, in figure 15 one can deduce, especially when one is on the site and can readily visualize the topographic "lie-of-the land," that the immediate path of subsurface water inflow into the seep is the draw upslope from the seep and that the exit is the swale to the southwest of the seep.

By expanding the mapping in the direction of the inflow path, one can begin to trace the source even further towards its origin. This information, along with judgment of the local terrain, can be used to appreciable advantage in identifying the general region of recharge. Familiarity with local conditions and experience will affect the degree of success using such a technique. Frequently, this kind of information is all that can be obtained, within the usual limitations of time, staff, and finances, to aid in planning remedial measures to control the growth of a saline-seep area or to prevent the continued development of an encroaching seep condition. Just exactly how the boundaries of the recharge area can be delineated with this EC mapping technique has not yet been thoroughly evaluated.

More details of this technique and an example of its use to identify the recharge of a saline seep are given in Appendix J.

CONCLUSIONS

Sufficient experience with the four-electrode soil EC_a technique has been obtained in northern Great Plains dryland agricultural areas to recommend its use for detecting and delineating bodies of salt-affected soil and the presence of encroaching saline-seep conditions. The technique employs a direct measure of the soil properties that are distinctive of saline-seep conditions, thus avoiding the uncertainties of indirect methods of saline-seep detection. The equipment needs are modest, training time is minimal, and the methods are simple and rapid.

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APPENDIX A

Glossary of Symbols and Abbreviations

a — Spacing between pairs of electrodes in the Wenner array, feet.

c — Current electrode, outside pair in Wenner configuration.

EC_e — Electrical conductivity of saturation paste extract of soil sample, mmho/cm.

EC_w — Electrical conductivity of water in field soil pores, mmho/cm.

EC_a — Apparent electrical conductivity of bulk soil, mmho/cm.

EC_x — Electrical conductivity of bulk soil within a given depth interval, mmho/cm.

EC_s — Electrical conductivity of bulk soil due to conductance of current via exchangeable cations, mmho/cm.

f_t — Factor for adjusting EC or R measurements made at various temperatures to a reference temperature of 25° C.

k Geometry constant for relating resistance measurements to electrical conductivity, cm^{-1}.

P Potential electrode, inside pair in Wenner configuration.

R_t Resistance of sample at its temperature, ohms.

SP Saturation percentage, percent water in soil at saturation.

[*T*] A dimensionless transmission coefficient, related to soil pore geometry, for relating the electrical conductivity of bulk soil, EC_a, to the electrical conductivity of water within the soil pores, EC_w.

t Temperature, ° C.

APPENDIX B

Table 3.--*Constants for converting English units to metric units*

[To obtain equivalent metric units, multiply English units by factor]

English unit	Factor	Metric unit
Inch	2.54	Centimeter
Foot	0.305	Meter
Cubic inch	16.387	Cubic centimeter
U.S. gallon	3.785	Liter
Ounce (avoirdupois)	28.3496	Gram
Pound (avoirdupois)	453.593	Gram
12-gage electrical wire (AWG)	---	2.1 ml
18-gage electrical wire (AWG)	---	1.0 ml

APPENDIX C

Measuring the Electrical Conductivity of Saturation Extracts and Other Water Samples

Soil salinity is conventionally measured and expressed in terms of the EC of a saturation paste extract of soil (*28*).

A saturated soil paste is prepared by adding distilled water to a sample of soil (0.5 to 1 lb) while stirring with a spatula. Because soils puddle most readily when worked at moisture contents near field capacity, sufficient water should be added immediately to bring the sample nearly to saturation.

The addition of water is continued until a saturated, uniform, soil-water paste, free of clumps, forms. At this point, the soil paste glistens as it reflects light, flows slightly when the container is tipped (or when a trench is formed in the paste with the flat side of the spatula and the paste is consolidated by tapping or jarring the container) and slides freely and cleanly off the spatula. After mixing, the sample should be allowed to stand, preferably overnight, but at least for an hour, and then the criteria for saturation should be rechecked. Free water should not collect on the soil surface nor should the paste stiffen markedly or lose its glisten. If the paste is too dry, remix with more water. If the paste is too wet, additional dry soil should be added and the paste remixed.

Initially, the soil sample can be air-dry or at field-moisture content, but the mixing process is generally easier if the soil is first air-dried and passed through a 2-mm (approximately 3/32-inch) sieve.

Sufficient water from the "equilibrated" saturation paste must be removed so that its electrical conductivity, EC_e, can be determined. This is usually accomplished with a filter funnel and vacuum. A convenient extraction unit for field use is shown in figure 19 (after J. D. Oster, U. S. Salinity Laboratory, Riverside, Calif., personal communication). A similar unit is now commercially available from GLA Agricultural Electronics Division, 4743 Brooks Street, Montclair, Calif. 91763. The saturated soil paste is transferred into the filter funnel with a filter paper in place, vacuum is provided with the hand pump, and extract is collected in the reservoir.

Figure 19.--Field extraction apparatus (Instant Salinity Tester, Model 32) and commercial bridge for determing EC_e in the field.

The EC of the saturation paste extract, EC_e, is then determined. Any EC meter may be used for this purpose. GLA makes a convenient unit (see fig. 19) that only requires a few drops of extract and reads directly in EC at 25° C. If sufficient sample is obtained (approximately 5 ml), its EC may be determined using the earth resistivity meter and a four-electrode cell (see fig. 20).

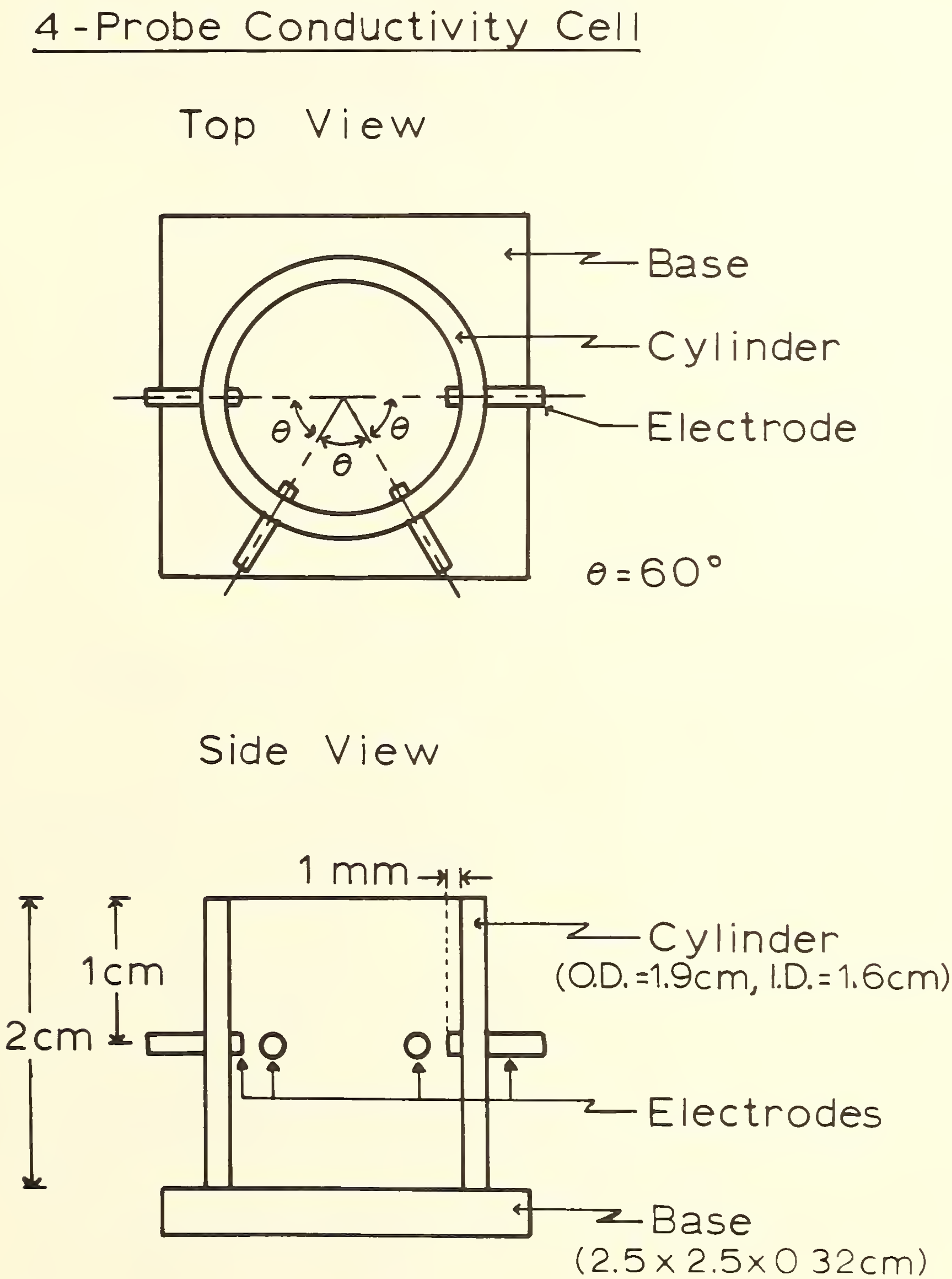


Figure 20--Construction schematic of four-electrode, conductivity cell used with the earth resistivity meter for determining EC of water samples (after *6*).

This unit can also be used for measuring the EC of surface, ground, irrigation water samples. The advantage of this unit is that those who have the four-electrode resistivity meter can use the same meter for salinity diagnoses for both soil and water in the field. The temperature of the water must be determined so that the EC can be corrected to 25° C as

$$EC_{25} = k\, f_t/R_t \qquad [9]$$

where k is the cell constant of the four-electrode conductivity cell (for methods of determining k values, see p. 89 in (*28*), f_t is the temperature conversion factor (see Appendix E), and R_t is the measured resistance of the cell filled with the water sample at temperature (t).

APPENDIX D

Sources and Descriptions of Required Four-Electrode Equipment

1. Earth resistivity meters

   Suitable meters include the following:

   a. Biddle model 63220-Megger Meter, handcranked generator. Approximate cost, $475.

      James G. Biddle Company
      Township Line & Jolly Roads
      Plymouth Meeting, Pa. 19462.

   b. Bison model 2350B-Earth resistivity meter, battery-operated generator. Approximate cost, $1,350.

      Bison Instruments, Incorporated
      5708 - 36th Street West
      Minneapolis, Minn. 55416.

   c. Soil Test model R-40-Strata Scout, battery-operated generator. Approximate cost, $975.

      Soil Test, Incorporated
      2205 Lee Street
      Evanston, Ill. 60202.

2. Electrodes and wire

   Electrodes may be of stainless steel, copper, brass, or other corrosion-resistant conductive metal. A convenient size and configuration is illustrated in figure 21. Also shown are the required wire connectors for the electrode and meter hookups. For general salinity appraisals to depths of 6 feet, wire lengths of 5 and 15 ft are needed for the potential and current electrodes, respectively (see Appendix F for distances between electrodes). This amount of wire can be wound on the electrode. When resistance measurements to deeper depths are desired, the wire is more conveniently stored on a spool that allows the wire to be quickly wound in and out. Such wire spools may be purchased from the resistivity meter manufacturers listed above or homemade units may be built like those shown

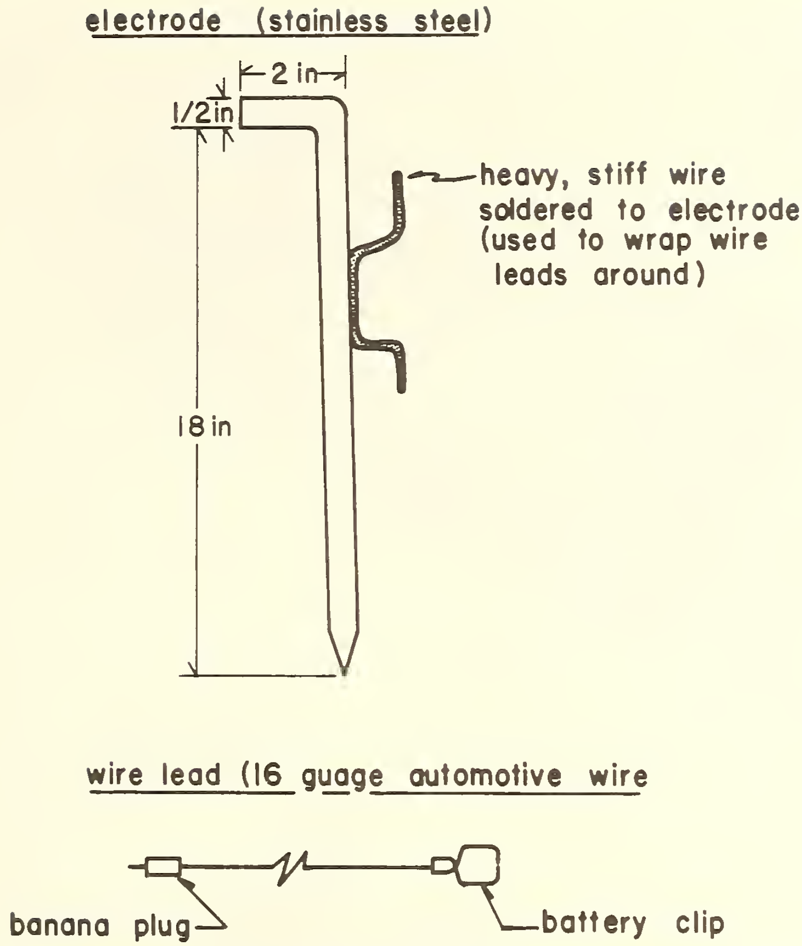


Figure 21.--Schematic of electrode and wiring for four-electrode measurements using the Wenner array method.

in figures 22 and 23. These units can be mounted on a tripod so that the meter and wire storage and retrieval systems can be used at near waist height.

3. EC-probe

The EC-probe of Rhoades and van Schilfgaarde (*20*) consists of four annular rings placed between insulators to form a probe, which is slightly tapered (1°) so that it can be inserted into the hole made by an Oakfield soil sampler (Oakfield Soil Sampling Kit, Soil Test, Inc.). The unit can be used with any earth resistivity meter. A construction schematic of the unit is presented in figure 24. The EC-probe is commercially available for about $100 from

Micron Engineering and Manufacturing, Inc.
977 Main Street
Riverside, Calif. 92501.

4. Miscellaneous equipment

A soil temperature probe is needed to measure soil temperature so that EC values can be corrected to 25° C (see Appendix E). Simple units such as the Tel-Tru model T-2210-5 thermometer can be used. Approximate cost, $15.

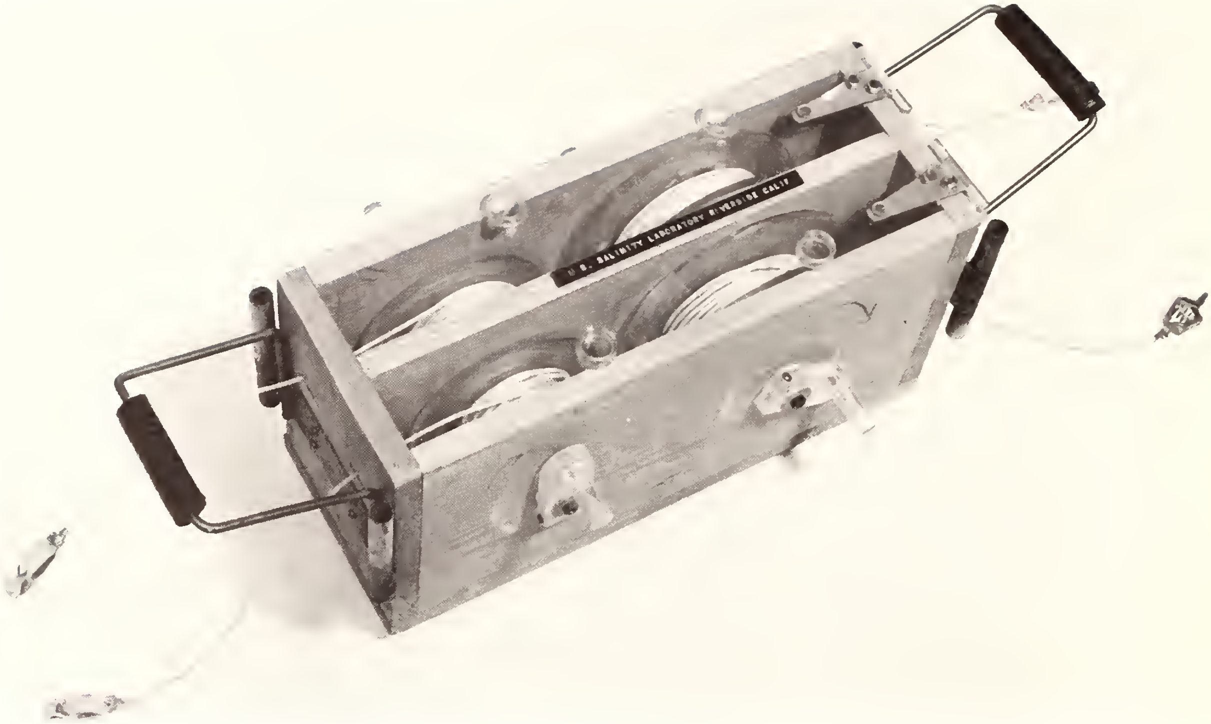


Figure 22.--Homemade wire-spool unit for use with Wenner array equipment.

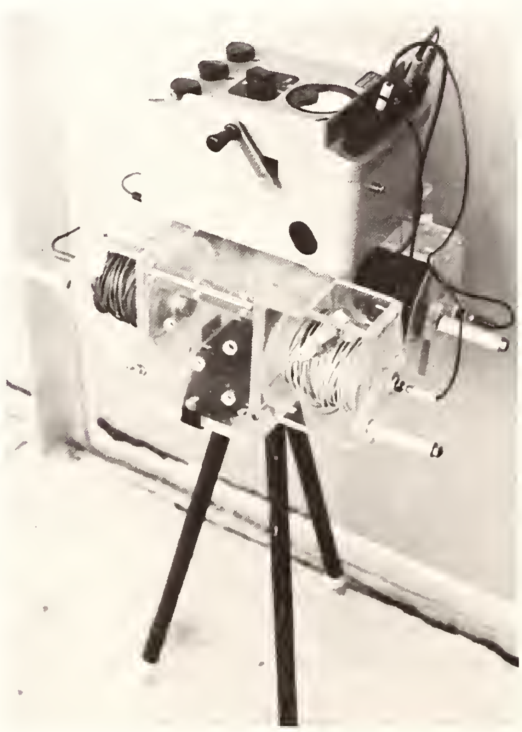
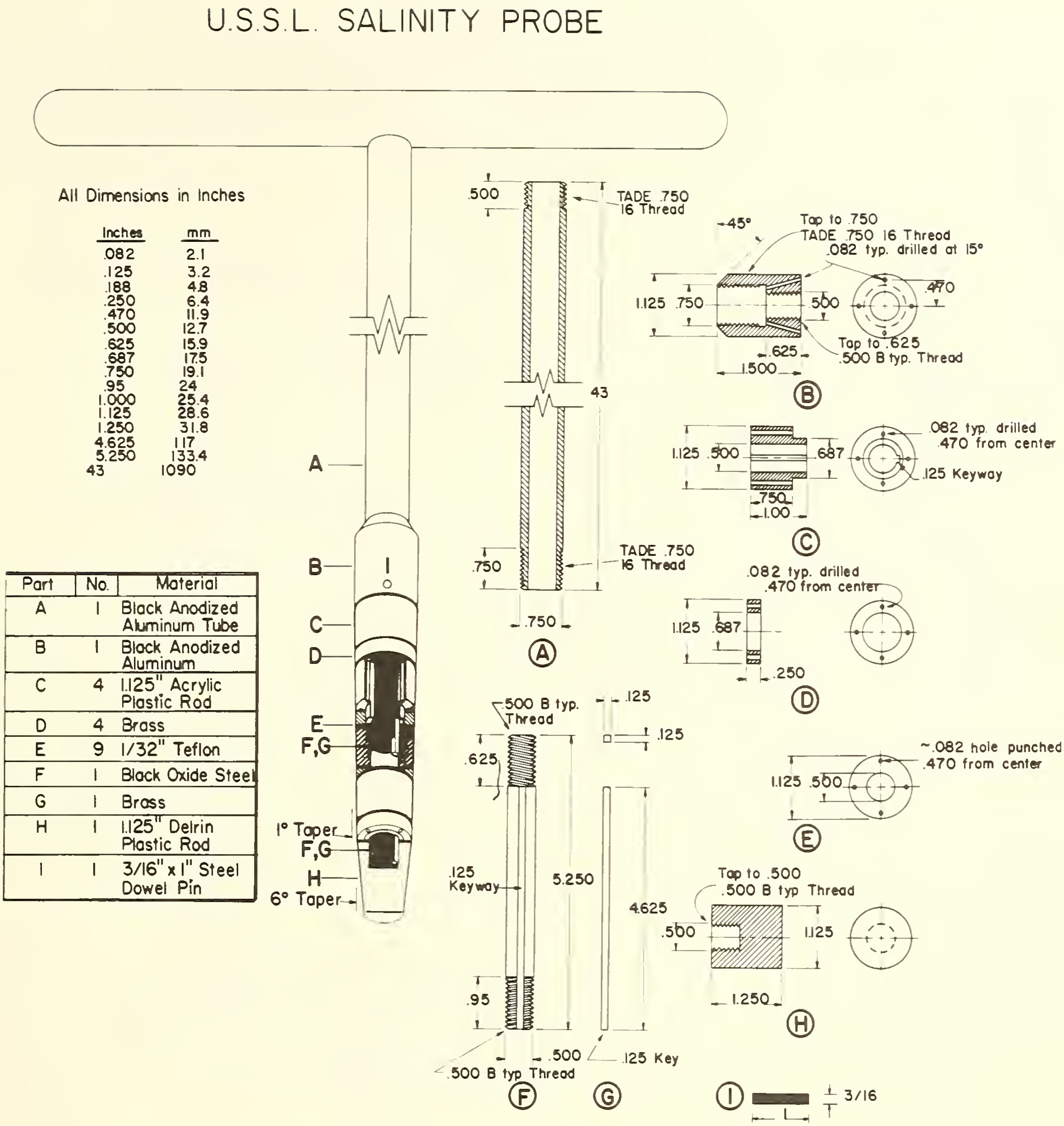


Figure 23.--Homemade, wire-spool unit (with tripod attachment and resistance meter shown in place) for use with Wenner array equipment.



Inches	mm
.082	2.1
.125	3.2
.188	4.8
.250	6.4
.470	11.9
.500	12.7
.625	15.9
.687	17.5
.750	19.1
.95	24
1.000	25.4
1.125	28.6
1.250	31.8
4.625	117
5.250	133.4
43	1090

Part	No.	Material
A	1	Black Anodized Aluminum Tube
B	1	Black Anodized Aluminum
C	4	1.125" Acrylic Plastic Rod
D	4	Brass
E	9	1/32" Teflon
F	1	Black Oxide Steel
G	1	Brass
H	1	1.125" Delrin Plastic Rod
I	1	3/16" x 1" Steel Dowel Pin

Figure 24.--Construction schematic of EC-probe (after *20*).

Tel-Tru Manufacturing Company
Rochester, N.Y.

More precise and convenient digital, soil temperature probes can be used where justified.

Temperatures usually need only be taken once a day at the midpoints of the first and second foot of soil.

At least one tape measure is required, but two are more convenient. Use a pin to hold the two tape ends in place at the center of the site, as shown in figure 1, so that electrode positions can be located and alined easily during electrode movement. Appropriate distances from the center position of the site for the potential (*P*) and current (*C*) electrodes for the Wenner array method (see fig. 6) are given in Appendix F and illustrated in figure 25. The tapes should be nonmetallic to prevent accidental "shorting" between electrodes.

Any pocket calculator may be used for field calculations. Calculations should be made on the spot to prevent the need for returning to check for apparent misreadings or questionable results. Programmable calculators are especially convenient for solving equation [8].

Notebooks for data collection, graph paper, ruler, and clipboards are needed for plotting and systematically tabulating data.

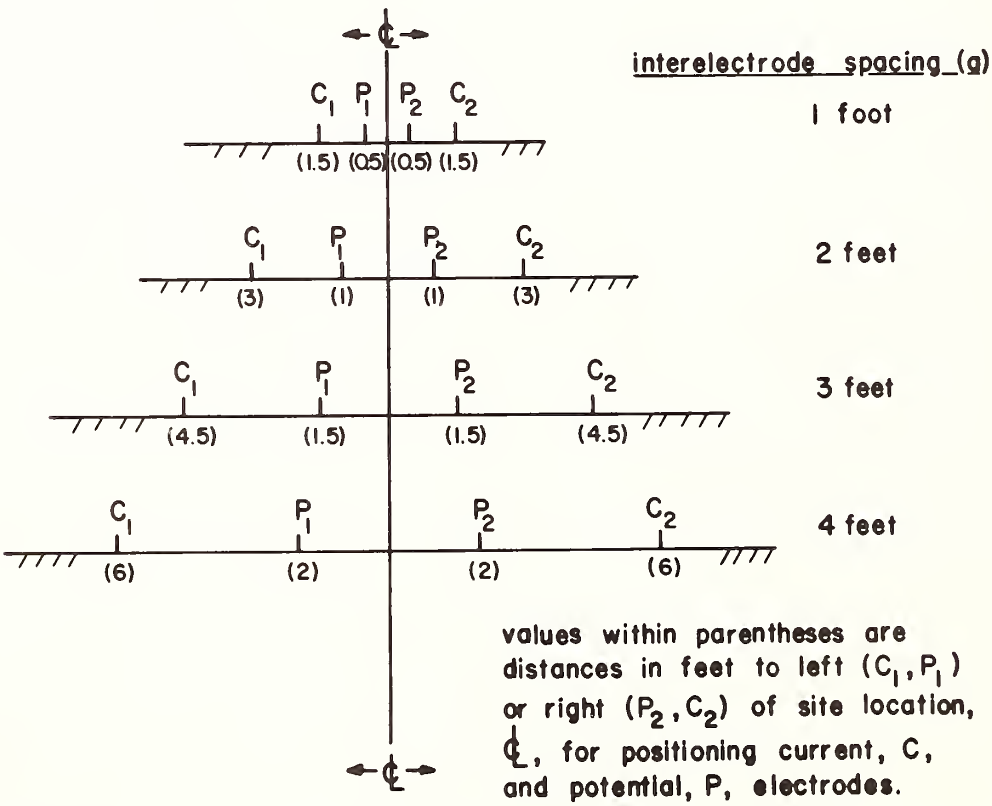


Figure 25.--Schematic showing placement of current (C_1, C_2) and potential (P_1, P_2) electrodes in the Wenner array.

Table 4.--*Temperature factors (f_t) for correcting resistance and conductivity data to the standard temperature of 25° C. (After U.S. Salinity Laboratory Staff, 28.)*

°C	°F	F_t	°C	°F	F_t
3.0	37.4	1.709	25.0	77.0	1.000
4.0	39.2	1.660	25.2	77.4	.996
5.0	41.0	1.613	25.4	77.7	.992
6.0	42.8	1.569	25.6	78.1	.988
7.0	44.6	1.528	25.8	78.5	.983
8.0	46.4	1.488	26.0	78.8	.979
9.0	48.2	1.448	26.2	79.2	.975
10.0	50.0	1.411	26.4	79.5	.971
11.0	51.8	1.375	26.6	79.9	.967
12.0	53.6	1.341	26.8	80.2	.964
13.0	55.4	1.309	27.0	80.6	.960
14.0	57.2	1.277	27.2	81.0	.956
15.0	59.0	1.247	27.4	81.3	.953
16.0	60.8	1.218	7.6	81.7	.950
17.0	62.6	1.189	27.8	82.0	.947
18.0	64.4	1.163	28.0	82.4	.943
18.2	64.8	1.157	28.2	82.8	.940
18.4	65.1	1.152	28.4	83.1	.936
18.6	65.5	1.147	28.6	83.5	.932
18.8	65.8	1.142	28.8	83.8	.929
19.0	66.2	1.136	29.0	84.2	0.925
19.2	66.6	1.131	29.2	84.6	.921
19.4	66.9	1.127	29.4	84.9	.918
19.6	67.3	1.122	29.6	85.3	.914
19.8	67.6	1.117	29.8	85.6	.911
20.0	68.0	1.112	30.0	86.0	.907
20.2	68.4	1.107	30.2	86.4	.904
20.4	68.7	1.102	30.4	86.7	.901
20.6	69.1	1.097	30.6	87.1	.897
20.8	69.4	1.092	30.8	87.4	.894
21.0	69.8	1.087	31.0	87.8	.890
21.2	70.2	1.082	31.2	88.2	.887
21.4	70.5	1.078	31.4	88.5	.884
21.6	70.9	1.073	31.6	88.9	.880
21.8	71.2	1.068	31.8	89.2	.877
22.0	71.6	1.064	32.0	89.6	.873
22.2	72.0	1.060	32.2	90.0	.870
22.4	72.3	1.055	32.4	90.3	.867
22.6	72.7	1.051	32.6	90.7	.864
22.8	73.0	1.047	32.8	91.0	.861
23.0	73.4	1.043	33.0	91.4	.858
23.2	73.8	1.038	34.0	93.2	.843
23.4	74.1	1.034	35.0	95.0	.829
23.6	74.5	1.029	36.0	96.8	.815
23.8	74.8	1.025	37.0	98.6	.801
24.0	75.2	1.020	38.0	100.2	.788
24.2	75.6	1.016	39.0	102.2	.775
24.4	75.9	1.012	40.0	104.0	.763
24.6	76.3	1.008	41.0	105.8	.750
24.8	76.6	1.004	42.0	107.6	.739

APPENDIX F

Placement of Potential and Current Electrodes When Using the Wenner Array Method and Calculation Factors Used to Calculate EC_a

Placement of the current (C_1 C_2) and potential (P_1 P_2) electrodes are conveniently made using two tapes spread outward from the center of location (C), as shown in figure 6. The left (C_1 P_1) and right (P_2 C_2) pairs of electrodes are positioned as illustrated in figure 25 and table 5.

Table 5.--*Distances, in feet from the center of the Wenner array span, for inserting the potential (P) and current (C) electrodes for various a spacings (in feet) and appropriate values of* $\left(\frac{5.222}{a}\right)$ *for use in equation* 6

a	*P*	*C*	$\left(\frac{5.222}{a}\right)$	*a*	*P*	*C*	$\left(\frac{5.222}{a}\right)$
Feet	*Feet*	*Feet*	Cm^{-1}	*Feet*	*Feet*	*Feet*	Cm^{-1}
1	0.5	1.5	5.222	25	12.5	37.5	0.209
2	1.0	3.0	2.611	26	13.0	39.0	.201
3	1.5	4.5	1.741	28	14.0	42.0	.187
4	2.0	6.0	1.306	30	15.0	45.0	.174
5	2.5	7.5	1.044	32	16.0	48.0	.163
6	3.0	9.0	.870	34	17.0	51.0	.154
8	4.0	12.0	.653	36	18.0	54.0	.145
10	5.0	15.0	.522	38	19.0	57.0	.137
12	6.0	18.0	.435	40	20.0	60.0	.131
14	7.0	21.0	.373	45	22.5	67.5	.116
15	7.5	22.5	.348	50	25.0	75.0	.104
16	8.0	24.0	.326	55	27.5	82.5	.095
18	9.0	27.0	.290	60	30.0	90.0	.087
20	10.0	30.0	.261	65	32.5	97.5	.080
22	11.0	33.0	.237	70	35.0	105.0	.075
24	12.0	36.0	.218				

APPENDIX G

Methods for Establishing EC_e vs. EC_a Calibrations

Using Wenner Array (*16*)

In this method, EC_a measurements with an interelectrode spacing of 1 ft are made at numerous field locations to obtain a suitable range in soil salinity and sampling population to establish a calibration. Since soil salinity typically varies from spot to spot and with depth in saline soils, several soil samples should be taken from the 0- to 1-ft soil depth in the line of electrodes

and within the center two-thirds of the spread of electrodes at each site. This composite soil sample is then used to obtain the average EC_e value (see Appendix C) corresponding to the field measured EC_a value.

A graphical plot of EC_e vs. EC_a is then made of the data, and the line of best fit is drawn through the points (either by eye or using statistical regression analysis) to establish the calibration (as shown in fig. 9). The calibration is limited to whatever range of soil salinities one can find in the location for the soil type in question. The accuracy is limited by the fact that the regions in a field where salinity is high are usually also wetter than in regions where salinity is low; this effect of variations in water content among samples tends to lower the slope yielding an elevated intercept. A much larger volume of soil is measured in the EC_a determinations than is sampled for EC_e determination. Thus, another limitation in the accuracy of this method is the degree to which the small soil sample truly represents the properties of the larger volume of soil. These errors have no adverse affect on general, practical salinity appraisals (A. D. Halvorson and others, manuscript in preparation).

Using Four-Electrode Cell (*18*)

A more accurate calibration than that possible with the conventional method can be obtained using four-electrode conductivity cells. Undisturbed soil cores are taken from field sites representative of the soil type for which the calibration is desired, using lucite column sections as corer inserts. A four-electrode cell is obtained by slicing through the soil core, removed from the corer, between adjacent plastic cylinder segments and then inserting the electrodes into tapped holes in the cell wall (see fig. 26). The EC_a of the soil is then determined using the resistivity meter. The cell constant (k) of the four-electrode cells is obtained by filling them with standard EC solutions

Figure 26.--Four-electrode conductivity cell after removal from the corer, segmentation, and insertion of electrodes (after *18*).

(EC_{25}) and measuring the cell resistance (R_t) using equation [9],

$$k = EC_{25} \cdot R_t \cdot 1/f_t$$

where f_t is given in Appendix E (*28*). After the EC_a is measured, the soil is removed and its EC_e determined as described in Appendix C. The EC_e vs. EC_a calibration is then established as described previously under "Using Wenner Array (*16*)." This method improves the accuracy of the calibration compared to the Wenner array method because exactly the same bulk volume of soil is used to measure both EC_a and EC_e. However, the method still suffers some of the other limitations described for the Wenner array method. To overcome these, the segmented column cells can be artificially leached with saline solutions to generate the desired range of salinities and adjusted to field capacity water content using pressure plate apparatus as described by Rhoades et al. (*19*) before determining EC_a and EC_e. Undisturbed cores can also be taken from soils adjusted to desired salinities and water content as described in EC-probe method, which follows.

Using EC-Probe (*20*)

The simplest method of establishing EC_e vs. EC_a calibrations makes use of the soil EC-probe to determine the EC_a value of small bodies of soil that have been adjusted in the field to give a desired range of salinities. To adjust salinity, saline waters of various salinities (EC = 4, 10, 20, 40; sodium adsorption ratio[8] = 8) are impounded in column sections (1 ft in diameter by 1.5 ft long) driven about 4 to 6 inches into the soil and a surrounding 6-inch-wide excavated moat. (About 10 gallons of saline water is required to bring the soil to a depth of 1 ft beneath the impounded area to the desired level of salinity.

When the soil has drained to about "field capacity," (that is, the reference water content), 2 or 3 days later, a soil sample is removed from the salinized body of soil (0 to 1 ft) with an Oakfield soil sampler. The soil EC-probe is centered in the sample hole, and the EC_a value corresponding to the 0- to 1-ft depth interval is determined. After the probe is removed, a soil sample (0 to 1 ft) is then taken of the soil volume surrounding the hole, using a 6-inch diameter barrel auger. The top 3 inches of soil are discarded. The EC_e of this soil sample is then used to measure EC_e and to establish the EC_e vs. EC_a relation for that soil type and reference water content. The above sequence of operations is illustrated in figures 27, 28, 29, and 30.

This calibration procedure is by far the quickest. Although one must wait a few days while the soil drains, the actual time spent in the field--setting up the leaching columns, adding the salinizing waters, determining EC_a, and taking soil samples--should not exceed 1 hour per calibration location. Only three or four EC_a readings and soil sample EC_e's need to be determined at any calibration location. Very satisfactory calibrations may be obtained (*20* and A. D. Halvorson and others and J. D. Rhoades and others, manuscripts in preparation).

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[8] $SAR = Na^+ / \sqrt{(Ca^{++} + Mg^{++})/2}$, where concentrations are in milliequivalents per liter.

Figure 27.--Cylinder and surrounding moat with impounded saline water used to leach soil and adjust it to a desired level of salinity.

Figure 28.--Access hole being made in soil with Oakfield soil sampling tube for subsequent insertion of EC-probe.

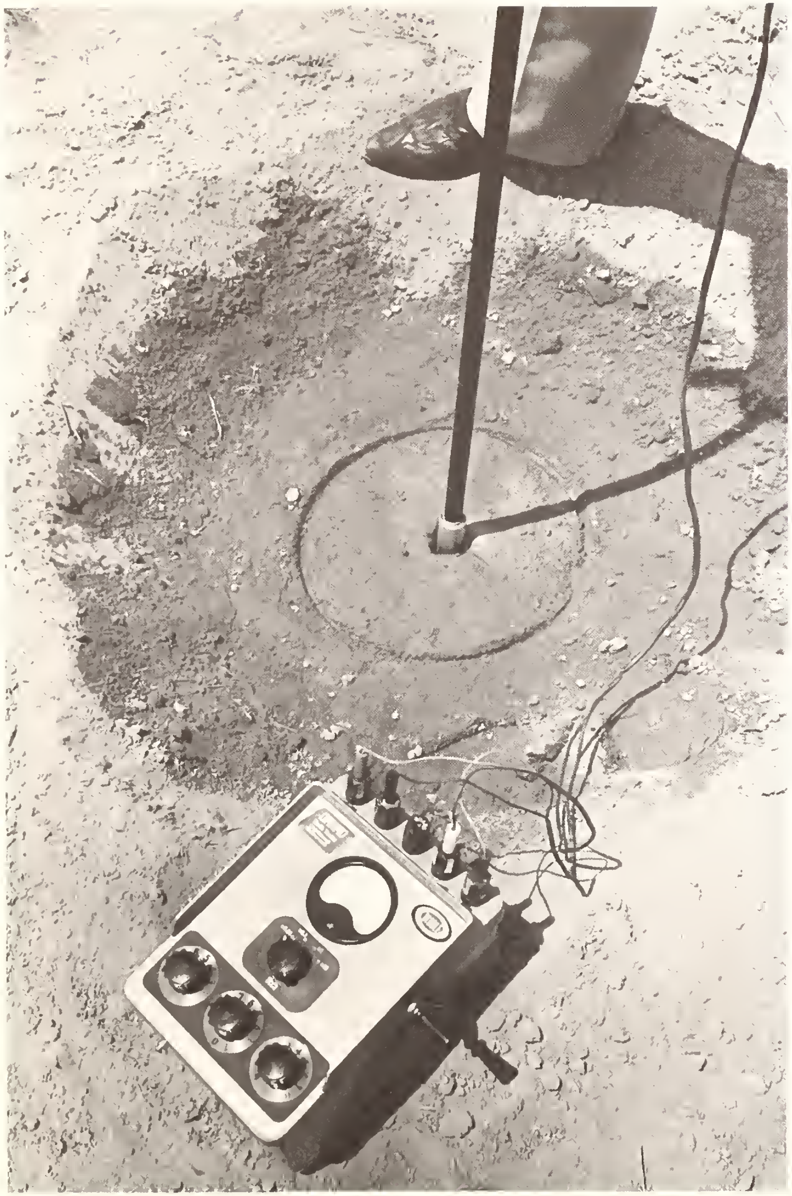

Figure 29.--EC-probe being inserted into salinity-adjusted soil for determination of EC_a.

Figure 30.--Sample being removed of salinized soil for subsequent determination of its EC_e.

The saline solutions for leaching the soil are made up of the concentrations of cations and salts shown in table 6. Any available grade of salt can be used for this purpose; for example, table salt can be used for NaCl and dessicant or deicing salt for $CaCl_2$.

Table 6.--*Concentrations and amounts of salts used to make up salinizing solutions*

Approximate EC	Sum of cations	$Ca^{++} + Mg^{++}$	Na^{++}	Amount per 10 gal	
				NaCl	$CaCl_2$
Mmhos/cm	*Meq/l*	*Meq/l*	*Meq/l*	*Pounds*	*Pounds*
4	40	17	23	0.11	0.10
10	100	57	43	.21	.35
20	200	135	65	.32	.83
40	400	300	100	.49	1.84

APPENDIX H

Salt Tolerance Parameters of Common Crops of the Northern Great Plains

Salt tolerance parameters for major agronomic crops grown in the northern Great Plains are listed in table 7 after Maas and Hoffman (*27*).

Table 7.--*Salt tolerance parameters of crops*

Crop	*A*[1]	*B*[2]
	Mmho/cm	*Percent mmho/cm*
Alfalfa	2.0	7.3
Barley (forage)[3]	6.0	7.1
Barley (grain)[3]	8.0	5.0
Bean (field)	1.0	19.0
Broadbean	1.6	9.6
Clover, alsike and red	1.5	12.0
Corn (forage)	1.8	7.4
Corn (grain)	1.7	12.0
Cowpea	1.3	14.0
Fescue, tall	3.9	5.3
Flax	1.7	12.0
Meadow foxtail	1.5	9.6
Orchardgrass	1.5	6.2
Potato	1.7	12.0
Ryegrass, perennial	5.6	7.6
Soybean	5.0	20.0
Sudangrass	2.8	4.3
Sugarbeet[4]	7.0	5.9
Trefoil, birdsfoot narrowleaf	5.0	10.0
Vetch	3.0	11.0
Wheat (grain)[3]	6.0	7.1
Wheatgrass, crested	3.5	4.0
Wheatgrass, fairway	7.5	6.9
Wheatgrass, tall	7.5	4.2
Wildrye, beardless	2.7	6.0

[1] EC_e at initial yield decline (threshold).

[2] Percentage yield decline per mmho/cm exceeding threshold.

[3] EC_e should not exceed 4 or 5 mmho/cm during emergence and seedling stage.

[4] EC_e should not exceed 3 mmho/cm during germination.

APPENDIX I

Sample Data and Calculations of EC_a, EC_x, and Accumulative EC_a

Sample field data, consisting of site identification, spacing *a*, and soil resistance R_t (soil temperature was 25° C) along with calculated values of EC_a, EC_x, and accumulated EC_a, are given in table 8 to aid in illustrating the calculation procedures. These *a* spacings are those that should be used for information about deep profile properties.

Table 8.--*Example data for sites A-D*

a spacing	R_t	EC_a	EC_x	Accumulative EC_a	
				Δa = 1 ft	Δa = 2 ft
Feet	*Ohms*	*Mmhos/cm*	*Mmhos/cm*	*Mmhos/cm*	
1	17.40	0.30	0.30	0.30	-
2	5.67	.46	.62	.76	0.46
3	2.89	.60	.89	1.36	-
4	1.78	.73	1.13	2.09	1.19
5	1.18	.89	1.49	2.98	-
6	.90	.97	-	3.95	2.16
7	.73	1.02	-	4.97	-
8	.58	1.13	-	6.10	3.29
9	.48	1.21	-	7.30	-
10	.42	1.24	-	8.55	4.53
12	.31	1.40	-	-	5.93
14	.27	1.38	-	-	7.31
15	.25	1.39	-	-	-
16	.22	1.48	-	-	8.80
18	.19	1.53	-	-	10.32
20	.17	1.54	-	-	11.86
25	.14	1.49	-	-	-
30	.12	1.45	-	-	-
35	.10	1.49	-	-	-
40	.10	1.31	-	-	-

EC_a Calculations

Using equation [6], $EC_a = 5.222\ f_t/a\ R_t$; for soil temperature = 25° C, f_t = 1.00 from Appendix E.

For a = 1 ft,

$$EC_{a\,(a=1)} = (5.222)\ (1)/(1)(17.4) = 0.30 \text{ mmhos/cm at } 25^\circ \text{ C}$$

For a = 2 ft,

$$EC_{a\,(a=2)} = (5.222)(1)/(2)(5.67) = 0.46 \text{ mmhos/cm at } 25^\circ \text{ C}$$

For a = 3 ft,

$$EC_{a\,(a=3)} = (5.222)(1)/(3)(2.89) = 0.60 \text{ mmhos/cm at } 25^\circ \text{ C}$$

Similarly, EC_a values are calculated for the other R_t, a data pairs. These values are tabulated above in table 8. Alternatively, the above calculations can be made by multiplying the values of (5.222/a) given in table 5 (Appendix F), for appropriate values of a, by f_t/R_t.

EC_x Calculations

Using equation [8],

$$EC_{x\,(0-1)} = EC_{a=1} = 0.30 \text{ mmhos/cm}$$

$$\begin{aligned} EC_{x\,(1-2)} &= [EC_{a=2} \times 2)-(EC_{a=1} \times 1)]/(2-1) \\ &= [(0.46 \times 2) - (0.30 \times 1)]/(2-1) \\ &= 0.62 \text{ mmhos/cm} \end{aligned}$$

$$\begin{aligned} EC_{x\,(2-3)} &= [(EC_{a=3} \times 3) - (EC_{a=2} \times 2)]/(3-2) \\ &= [(0.60 \times 3) - (0.46 \times 2)]/(3-2) \\ &= 0.88 \text{ mmhos/cm} \end{aligned}$$

Similarly, EC_x values are calculated for other intervals, although the method is not advised for depths greater than 5 ft because of the usual lack of homogeneity of soil properties in the lateral dimension encompassed at such wide a spacings. Such conditions may give negative EC_x values.

Accumulative EC_a Calculations

Accumulating EC_a values by an a spacing differential of 1 ft, accumulative $EC_{a\,(\Delta a=1)}$ is calculated for successive a spacings as follows:

a	EC_a	Accumulative $EC_{a(\Delta a = 1)}$
Feet	*Mmho/cm*	*Mmho/cm*
1	0.30	0.30
2	.46	0.30 + 0.46 = 0.76
3	.60	0.30 + 0.46 + 0.60 = 1.36
4	.73	0.30 + 0.46 + 0.60 + 0.73 = 2.10
5	.88	0.30 + 0.46 + 0.60 + 0.73 + 0.88 = 2.97
6	.97	0.30 + 0.46 + 0.60 + 0.73 + 0.88 + 0.97 = 3.94

Accumulating by an a spacing differential of 2 ft, accumulative $EC_{(\Delta a=2)}$ is calculated for successive a spacings as follows:

a	EC_a	Accumulative $EC_{a(\Delta a = 2)}$
Feet	*Mmho/cm*	*Mmho/cm*
2	0.46	0.46
4	.73	0.46 + 0.73 = 1.19
6	.97	0.46 + 0.73 + 0.97 = 2.16
8	1.13	0.46 + 0.73 + 0.97 + 1.13 = 3.29
10	1.24	0.46 + 0.73 + 0.97 + 1.13 + 1.24 = 4.53
12	1.40	0.46 + 0.73 + 0.97 + 1.13 + 1.24 + 1.40 = 5.93

Plots of EC_a vs. a or EC_x vs. midpoint of the soil depth interval allow one to diagnose the site type as explained in table 1. Such plots using the above sample data are shown in figures 31 and 32. The plots show that this site is not under the influence of a saline seep since EC_a, or EC_x, is low near the soil surface and increases with depth through the root zone.

Plots of accumulative EC_a values vs. a are useful for estimating the depth to a discontinuity in the profile as discussed in Appendix E. Such a plot, using the above sample data,is shown in figure 33. Best fit straight lines are drawn through the points. The a spacing(s) corresponding to the intersection of two such straight-line segments is taken as the estimate of the depth to a discontinuity in the soil profile, that is, a change in earth material properties or a water table. In this example, such a discontinuity (the occurrence of the dense glacial till deposit) occurs at a depth of about 8 ft.

APPENDIX J

Mapping Techniques and Method of Identifying the Direction of Ground Water Inflow to a Seep and Its General Recharge Area

Both near surface and subsurface salinity can be mapped by making four-electrode EC determinations at successive sites along a traverse or at grid

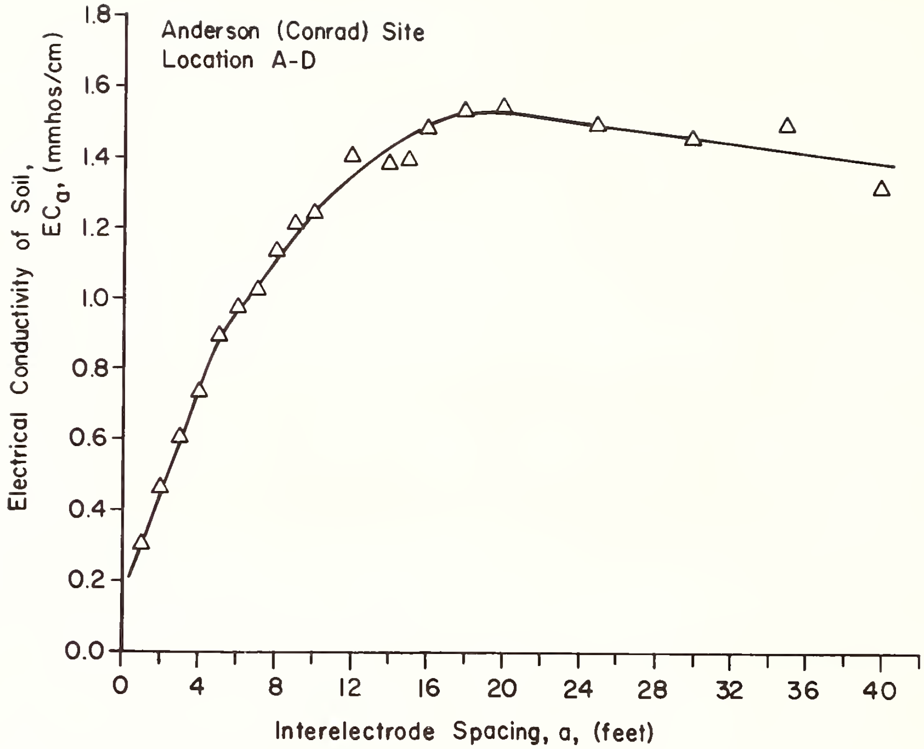

Figure 31.--Relation between soil EC, EC_a, and interelectrode spacing for an unaffected site near Conrad, Mont.

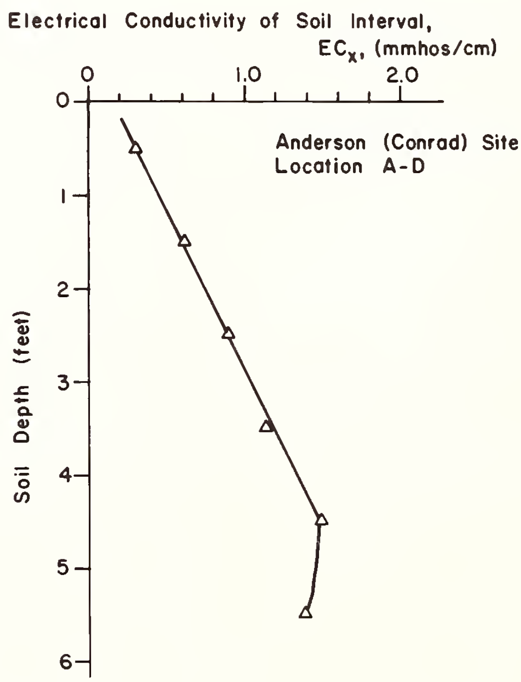

Figure 32.--Relation between EC_x and soil depth for a site near Conrad, Mont.

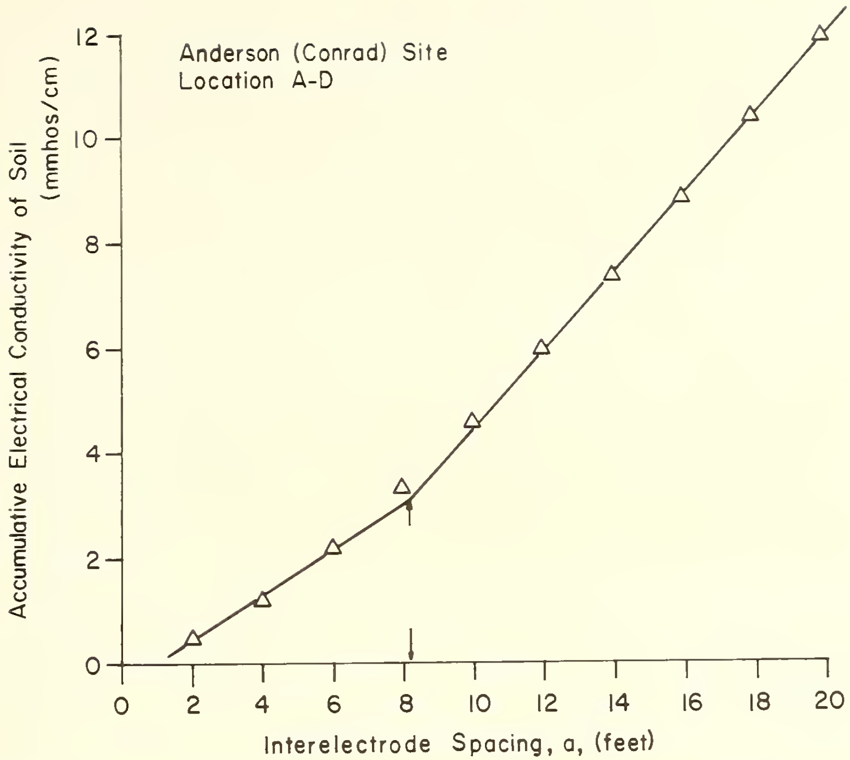

Figure 33.--Relation between accumulative EC_a and interelectrode spacing for a site near Conrad, Mont.

locations. A map is produced by displaying the data on a planar representation of grid points and drawing isolines of soil resistance, EC_a, EC_x, or EC_e, depending on purpose and preference. The spacing required between mapping stations depends on the detail and refinement desired for any particular case; a 100-ft distance is reasonable for most cases. The mapper should lay out an equal-sided grid network about the area of concern--as defined from preliminary EC_a determinations made by traversing the general area with a fixed-array rig--and make EC_a measurements at each grid point.

These EC measurements are used to map the surface and/or subsurface EC values and, to identify from the boundaries of high EC, the direction from which the saline water is entering the area. When this direction is determined, the grid pattern should be expanded in a direction counter to that of the inflow pattern and at right angles to this direction only as wide as necessary. By generating the map in this manner, the general source area of recharge to the seep can likely be deduced with little expenditure of time and effort.

The above technique is illustrated in figures 34 and 35, which represent maps of EC_x in and around a small, newly developed seep area near Conrad, Mont. This seep was situated on a side slope (sloping gradually downhill from the west to the east) between two knolls (to the north and south) and downslope from two apparent uphill, potential recharge "flats." One of the latter areas lay to the northwest of the seep, the other to the southwest.

We wanted to identify which "flat" was the contributing recharge area to the seep, or if both were, so that continuous cropping systems could be established where needed to aid in "drying-up" the seep. A grid of stakes was laid

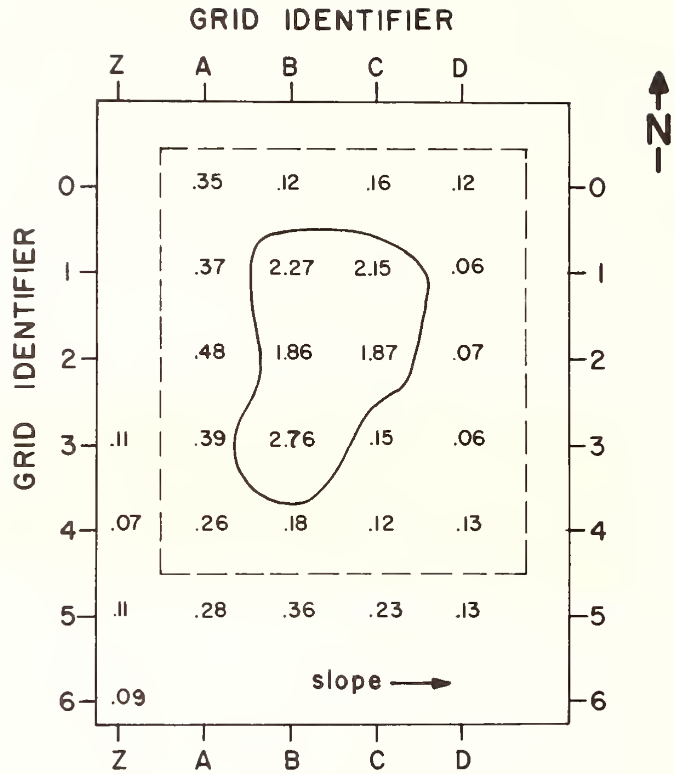

Figure 34.--Surface configuration of a saline seep. Values are EC_x (0 to 1 ft) in mmhos/cm.

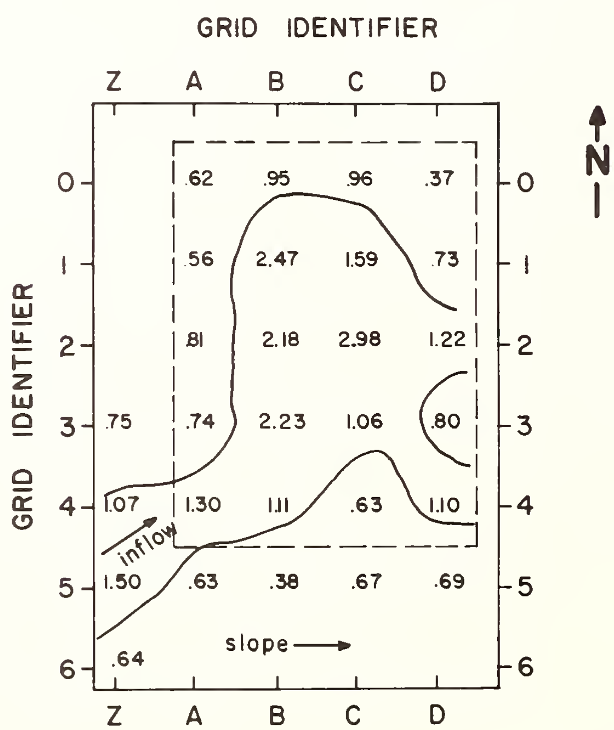

Figure 35.--Subsurface configuration of salt-affected soil. Values are EC_x (3 to 4 ft) in mmhos/cm.

out about the seep with a 100-ft interval. EC_x values were determined at each site for soil depths of 0 to 1, 1 to 2, 2 to 3, and 3 to 4 ft by taking EC_a readings with the Wenner array equipment at interelectrode spacings of 1, 2, 3, and 4 ft and using equation [8]. These EC_x values were then mapped.

Figure 34 shows how the seep configuration could be delineated from the surface EC measurements. The direction of ground water inflow could not be established from the surface EC_a information, but was readily discerned from the distribution of subsurface EC values, as shown in figure 35. The data obtained from the initial measurements shown within the dashed line, suggested that the direction of inflow was from the southwest.

Additional data were then obtained along the south and west boundaries of the previously mapped area. These data verified that, indeed, the direction of subsurface inflow was from the southwest. To further identify and delineate the recharge area, if desired or needed, additional and deeper EC_x values should be determined by further expanding this map in whatever direction it leads.

Although this example is simple, it demonstrates the principles of the recommended method, that is--

1. Make preliminary traverses and use the fixed array rig with an interelectrode spacing of 2 ft in the area of concern to locate the general area of salt-affected soil.

2. Begin to generate a map of EC_a or EC_x values at grid points established about the generally located area.

3. Connect points of equal values to delineate the subsurface configuration of the salt-affected body of soil.

4. Expand the measurements in the direction indicated by the EC isolines.

Use this subsurface information along with onsite topographical and physiographic surface evaluations (water flowing under gravity flows downslope) to identify the general area of recharge.

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